Technology Development for the Advanced Technology Large Aperture Space Telescope (ATLAST) as a Candidate Large UV-Optical-Infrared (LUVOIR) Surveyor

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Background

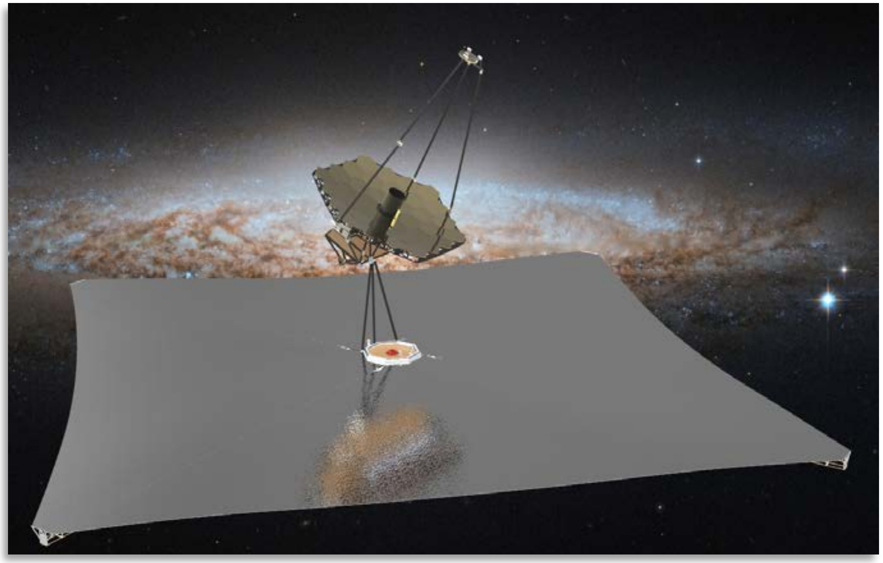
- 2009
  - ATLAST initial design study; proposed to 2010 Decadal Survey
- 2010
  - Decadal Committee recommends "a New Worlds Technology Development Program" as the highest priority medium-scale activity
- 2014
  - NASA Astrophysics 30-year Roadmap recommends a large UV-Optical-Infrared (LUVOIR) telescope in the "Formative Era"
- 2015
  - AURA releases *From Cosmic Birth to Living Earths*; recommends the High Definition Space Telescope (HDST) as a general astrophysics observatory with the "killer app" of detecting and characterizing habitable exoplanets
- Early to mid-2016
  - NASA Astrophysics Division initiates Science and Technology Definition Teams (STDTs) to perform detailed mission concept studies in preparation of the 2020 Decadal Survey: LUVOIR is one of four missions to be studied

What Is ATLAST?

- ATLAST, LUVOIR, HDST are all ***mostly*** interchangeable
  - LUVOIR is architecture non-specific
  - HDST advocates for a large segmented aperture
  - ATLAST has engineering reference designs for segmented and monolithic systems
  - All have very similar science goals

- A multi-institutional team to continues to study ATLAST
  - Multiple engineering reference designs, discussed in:

N. Rioux, “A future large-aperture UVOIR space observatory: reference designs”, paper 9602-4



ATLAST Science

- Detect and characterize a statistically significant population of habitable exoplanets
  - Discover dozens of exoEarths
  - Look for, and potentially confirm, presence of life
  - Observe general planet populations for comparative studies

- Perform a broad array of UVOIR general astrophysics:
  - Galaxy, star, and planet formation
  - Flow of material between galaxies
  - Observations within our own solar system

- ATLAST's science portfolio is very similar to that outlined in AURA's *From Cosmic Birth to Living Earths* report

Top-Level System Requirements

Parameter		Requirement	Stretch Goal	Traceability
Primary Mirror Aperture		≥ 8 meters	12 meters	Resolution, Sensitivity, Exoplanet Yield
Telescope Temperature		273 K – 293 K	-	Complexity, Fabrication, Integration & Test, Contamination, IR Sensitivity
Wavelength Coverage	UV	100 nm– 300 nm	90 nm – 300 nm	-
	Visible	300 nm – 950 nm	-	-
	NIR	950 nm – 1.8 µm	950 nm – 2.5 µm	-
	MIR	Sensitivity to 5.0 µm	-	Transit Spectroscopy
Image Quality	UV	< 0.20 arcsec at 150 nm	-	-
	Vis/NIR/MIR	Diffraction-limited at 500 nm	-	-
Stray Light		Zodi-limited between 400 nm – 1.8 µm	Zodi-limited between 200 nm – 2.5 µm	Exoplanet Imaging & Spectroscopy SNR
Wavefront Error Stability		< 10 pm RMS uncorrected system WFE per control step	-	Starlight Suppression via Internal Coronagraph
Pointing	Spacecraft	≤ 1 milli-arcsec	-	-
	Coronagraph	< 0.4 milli-arcsec	-	-

Technology Development for ATLAST

- Our team identified 5 key technology areas to enable the ATLAST mission:
  - Internal Coronagraph
  - Starshade
  - Ultra-stable large aperture systems
  - Detectors
  - Mirror Coatings

- Established a technology development roadmap
  - Identifies technology gaps
    - Includes current TRL and gap-type (*e.g.* technology, engineering, manufacturing)
  - Recommends development activities

Assumptions

- Assume a new mission start with PDR circa 2024
  - Technologies must be TRL 5 by PDR
  - Technology development plan must be credible in time for 2020 Decadal Survey

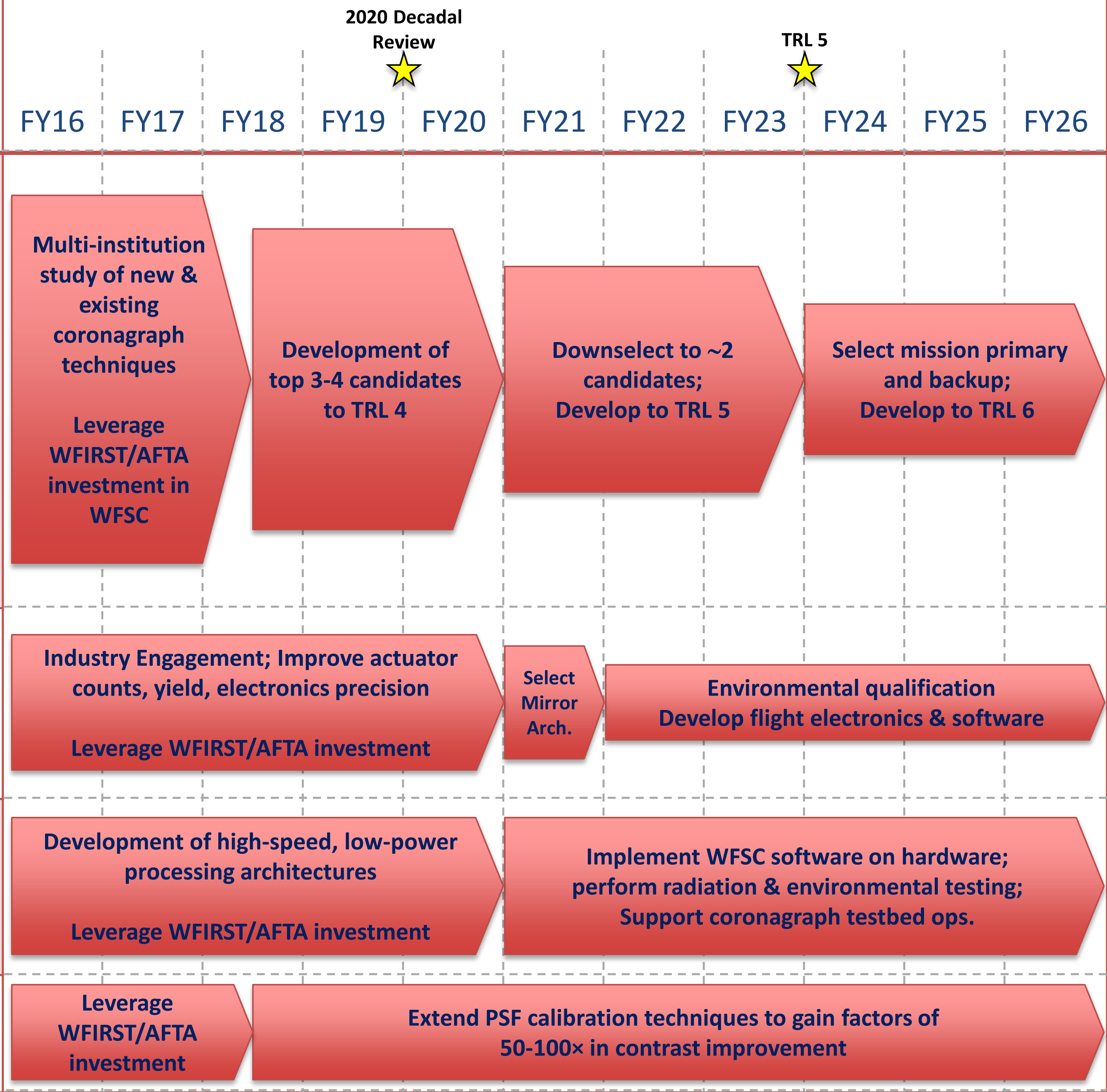
- Assume flexibility with respect to ATLAST architecture
  - Explore multiple solutions at this early stage of development
  - i.e. develop for both monolithic and segmented apertures, develop both internal coronagraphs and starshades, etc.

- Adopt a conservative approach in identifying gaps
  - This a systems-level problem: every technology impacts every other
  - Requires detailed integrated design cycles
  - For now, assume “worst case” and refine as technologies develop and modeling is performed

Technologies

Internal Coronagraph	Parameter	Need	Capability	Current TRL	Technology, Engineering, or Manufacturing
Broadband High-Contrast Coronagraph **includes Wavefront Sensing & Control (WFSC)**	Raw Contrast	1×10^{-10} (detect) 5×10^{-10} (char.)	3.2×10^{-10}	3	Technology
	IWA	3.6 λ/D (detect) 2.0 λ/D (char.)	3 λ/D		
	OWA	~ 64 λ/D	16 λ/D		
	Bandpass	10-20% (instantaneous) 400 nm – 1.8 µm (total) 200 nm – 2.5 µm (goal)	10%		
	Aperture	Obscured, segmented	Unobscured		
	WFSC	Fast, low-order, at stellar photon rates	Slow, tip/tilt, bright lab source		
Deformable Mirrors	Actuator count	128×128 (continuous) >3000 (segmented)	64×64 (continuous) <200 (segmented)	3	Engineering, Manufacturing
	Environmental	Robust, rad. hard	Testing underway		
	Electronics	>16 bits, high-throughput	~16 bit, dense cabling		
Autonomous Onboard Computation	Bandwidth	Closed-loop > a few Hz	Human-in-the-loop	3	Engineering, Manufacturing
	Electronics	Rad. hard, >100 GFLOPS/W	<20 GFLOPS/W		
Starlight Suppression Image Processing	PSF Calibration	Factor of 50-100× improvement in contrast	25× demonstrated 30× goal for WFIRST	3	Engineering

Internal Coronagraph



Broadband High-Contrast Coronagraph

includes Wavefront Sensing & Control (WFSC)

- Multi-institution study of new & existing coronagraph techniques

  Leverage WFIRST/AFTA investment in WFSC
- Development of top 3-4 candidates to TRL 4
- Downselect to ~2 candidates; Develop to TRL 5
- Select mission primary and backup; Develop to TRL 6

Deformable Mirrors

- Industry Engagement; Improve actuator counts, yield, electronics precision

  Leverage WFIRST/AFTA investment
- Select Mirror Arch.
- Environmental qualification
  Develop flight electronics & software

Autonomous Onboard Computation

- Development of high-speed, low-power processing architectures

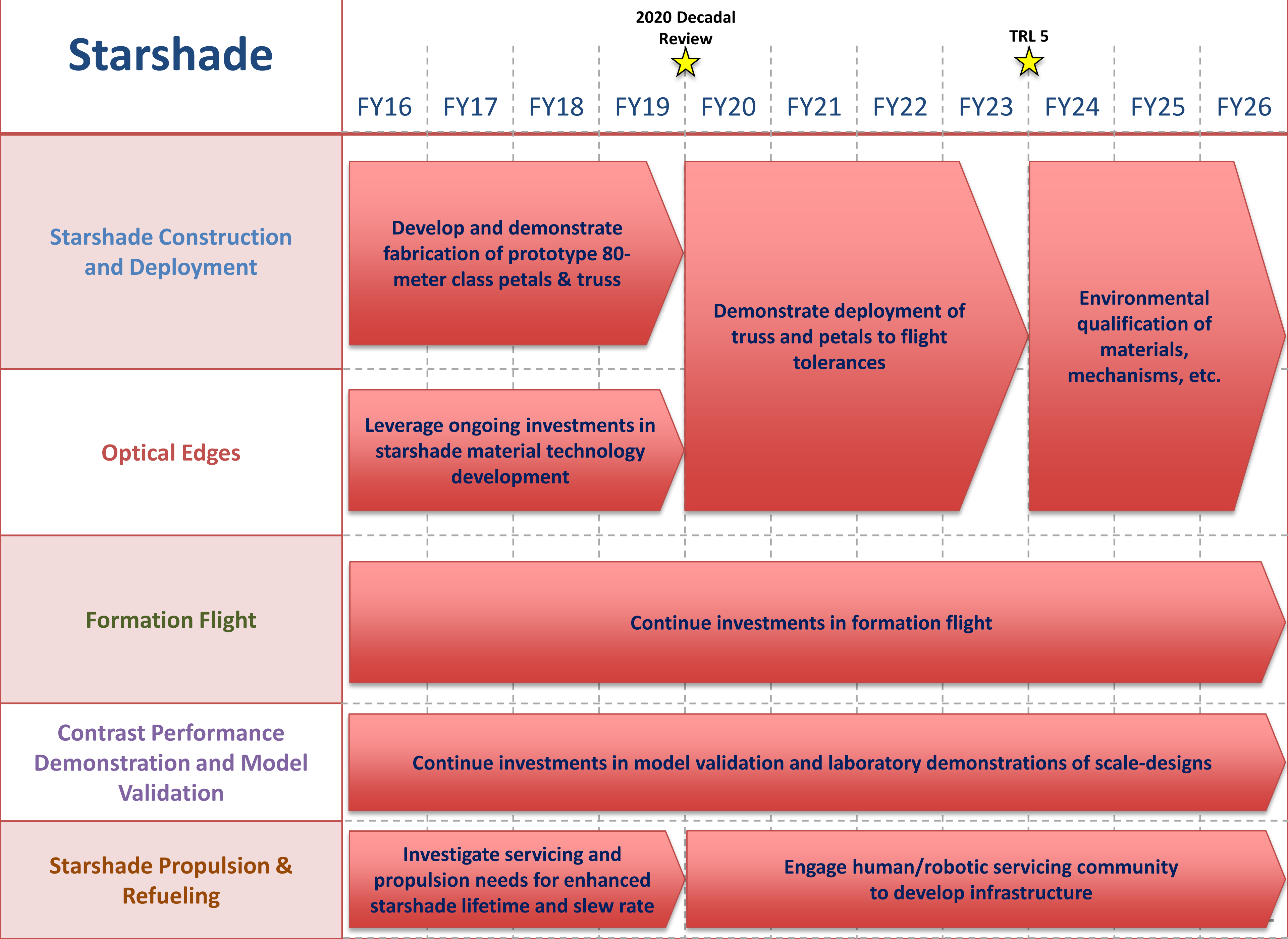
  Leverage WFIRST/AFTA investment
- Implement WFSC software on hardware; perform radiation & environmental testing; Support coronagraph testbed ops.

Starlight Suppression Image Processing

- Leverage WFIRST/AFTA investment
- Extend PSF calibration techniques to gain factors of 50-100× in contrast improvement

Starshade	Parameter	Need	Capability	Current TRL	Technology, Engineering, or Manufacturing
Starshade Construction and Deployment	-	Petal and central truss design consistent with an 80-m class starshade Demonstrate manufacturing and deployment tolerances	Demonstrated prototype petal for 40-m class starshade Demonstrated deployment tolerances with a 12-m Astromesh antenna with 4 petals	3	Engineering
Optical Edges	Edge radius	≤ 1 μm	≥ 10 μm	3	Technology
	Reflectivity	≤ 10%	-		
	Stowed radius	≤ 1.5 m	-		
Formation Flight	Lateral sensing error	≤ 20 cm	-	3	Engineering
	Peak-to-peak control	< 1 m	-		
	Centroid estimation	≤ 0.3% of optical resolution	≥ 1%		
Contrast Performance Demonstration and Model Validation	-	1×10^{-10} broadband contrast at Fresnel numbers ≤ 50	3×10^{-10} contrast, excluding petal edges, narrowband, at Fresnel number of ~500	3	Technology
Starshade Propulsion & Refueling	-	Propulsion & refueling to enable > 500 slews during 3 years of a 5-year mission	Requires study; robotic refueling appears feasible	3	Technology, Engineering

Starshade



2020 Decadal Review

TRL 5

FY16 FY17 FY18 FY19 FY20 FY21 FY22 FY23 FY24 FY25 FY26

Starshade Construction and Deployment

Develop and demonstrate fabrication of prototype 80-meter class petals & truss

Demonstrate deployment of truss and petals to flight tolerances

Environmental qualification of materials, mechanisms, etc.

Optical Edges

Leverage ongoing investments in starshade material technology development

Formation Flight

Continue investments in formation flight

Contrast Performance Demonstration and Model Validation

Continue investments in model validation and laboratory demonstrations of scale-designs

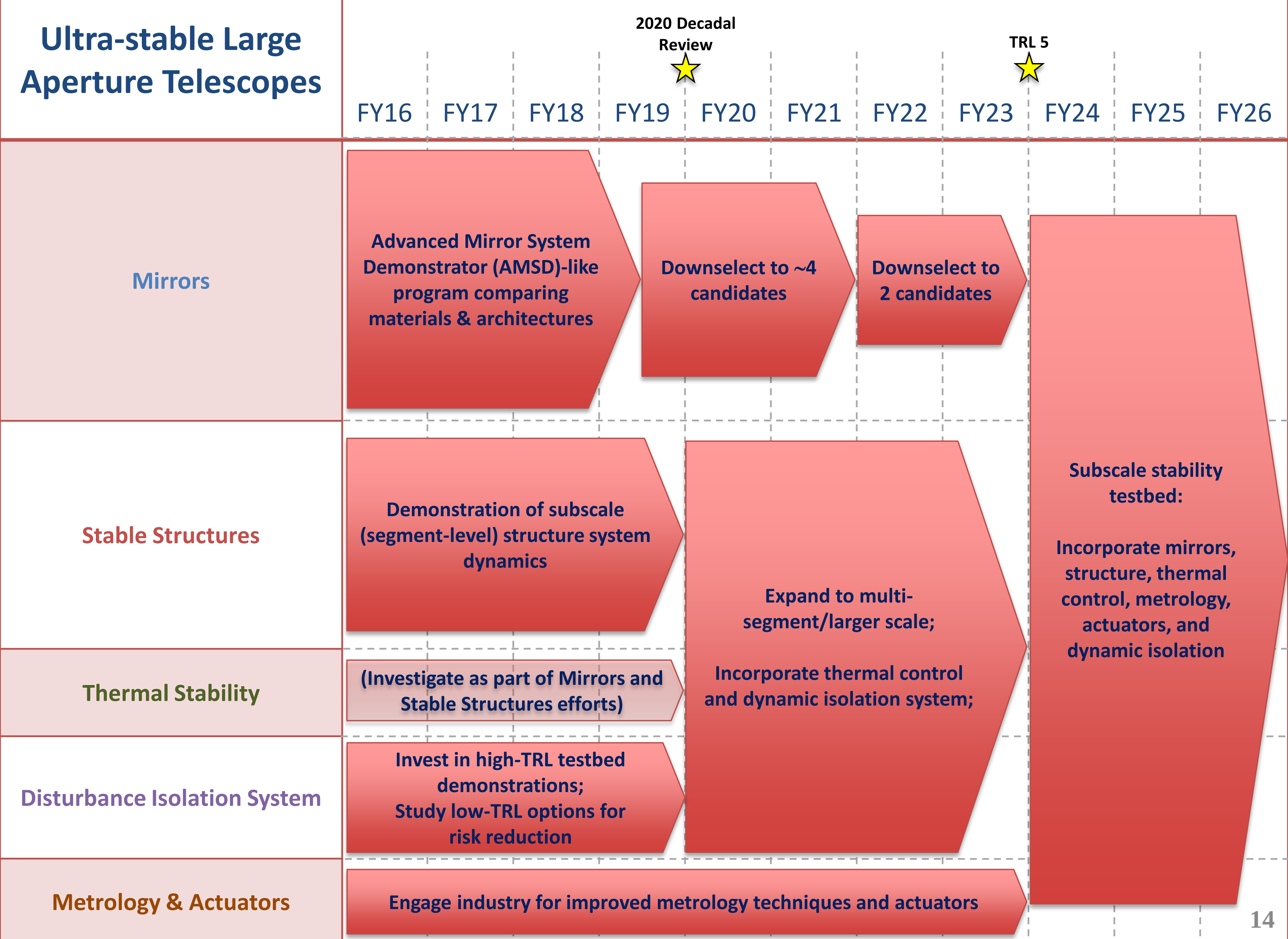
Starshade Propulsion & Refueling

Investigate servicing and propulsion needs for enhanced starshade lifetime and slew rate

Engage human/robotic servicing community to develop infrastructure

Ultra-stable Large Aperture Telescopes	Parameter	Need	Capability	Current TRL	Technology, Engineering, or Manufacturing
Mirrors	Areal Density	< 36 kg/m^2 (Delta IVH) < 500 kg/m^2 (SLS)	~12 kg/m^2 (SiC) ~35 kg/m^2 (ULE) ~70 kg/m^2 (JWST)	4	Engineering, Manufacturing
	Areal Cost	< \$2 M/m^2	~\$6 M/m^2 (JWST)		
	Areal Production Rate	30-50 m^2/year	~4 m^2/year (JWST) ~1 m^2/year (HST) ~100-300 m^2/year planned by TMT but not yet demonstrated		
Stable Structures	Moisture Expansion	Zero after initial moisture release	Continuous moisture release	3	Technology
	Lurch	< 10 pm / wavefront control step	Micro-lurch at joint interfaces		
	Metrology	High-speed picometer metrology to validate performance	Nanometer speckle interferometry on JWST		
Thermal Stability	Material Stability	~10 nm/K	~100 nm/K	3	Technology
Disturbance Isolation System	End-to-end Attenuation	140 dB at frequencies > 20 Hz	80 dB at frequencies > 40 Hz (JWST passive isolator only)	4	Technology, Engineering
Metrology & Actuators	Sensing Accuracy	~1 pm	~1 nm	4	Technology
	Control Accuracy	~1 pm	~5 nm		

Ultra-stable Large Aperture Telescopes



Mirrors

Advanced Mirror System Demonstrator (AMSD)-like program comparing materials & architectures

Downselect to ~4 candidates

Downselect to 2 candidates

Stable Structures

Demonstration of subscale (segment-level) structure system dynamics

Thermal Stability

(Investigate as part of Mirrors and Stable Structures efforts)

Disturbance Isolation System

Invest in high-TRL testbed demonstrations;
Study low-TRL options for risk reduction

Expand to multi-segment/larger scale;

Incorporate thermal control and dynamic isolation system;

Subscale stability testbed:

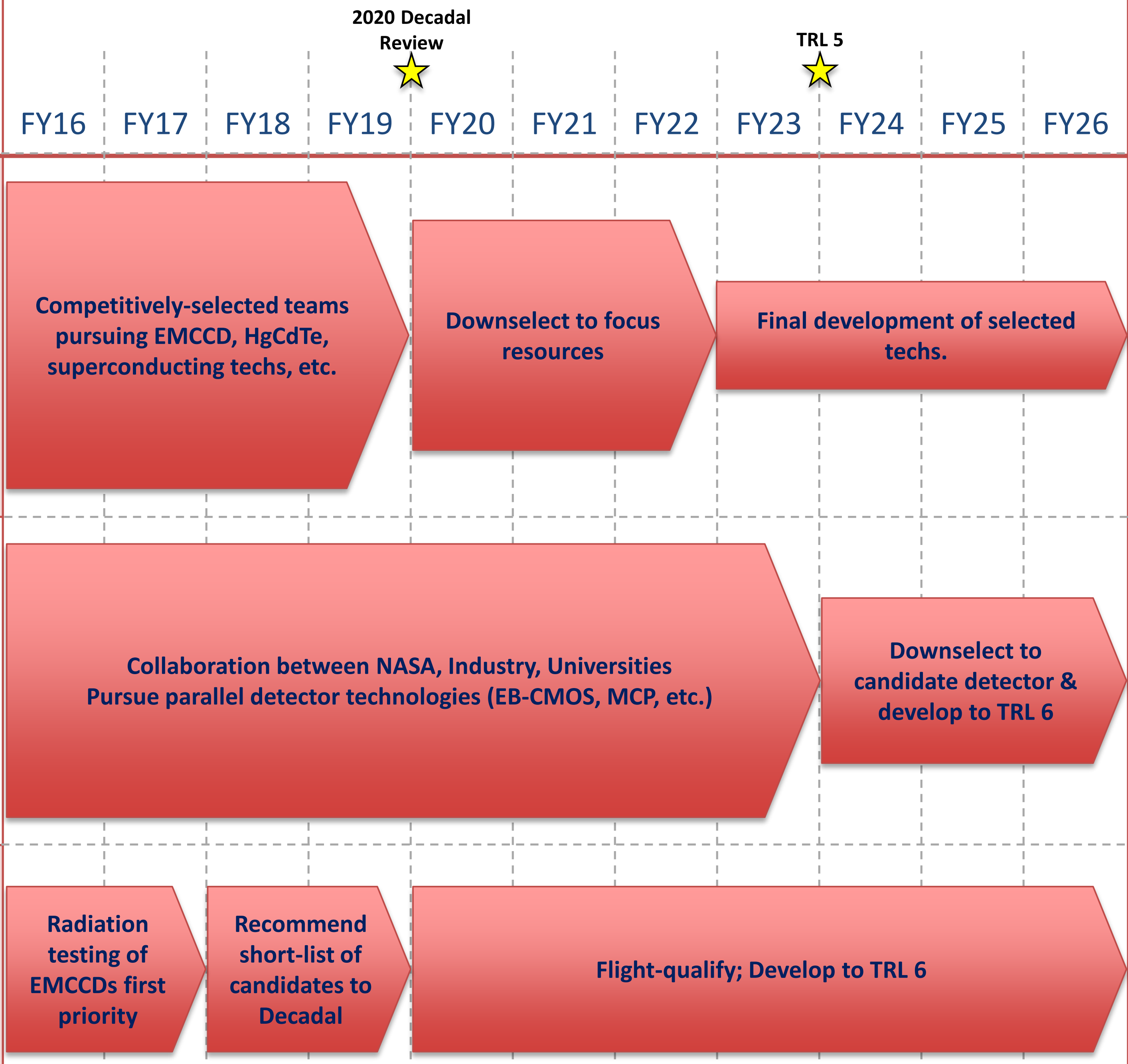
Incorporate mirrors, structure, thermal control, metrology, actuators, and dynamic isolation

Metrology & Actuators

Engage industry for improved metrology techniques and actuators

Detectors	Parameter	Need	Capability	Current TRL	Technology, Engineering, or Manufacturing
Visible-NIR Single-photon Detectors for Enabling Exoplanet Science	Bandwidth	400 nm – 1.8 µm (2.5 µm goal)	EMCCD is promising, need rad.-hard testing, has hard cutoff at 1.1 µm; HgCdTe APDs good for NIR but need better dark current; MKID & TES meet requirements but require cryo ops.	3-5	Technology, Engineering, Manufacturing
	Read Noise	<< 1 e^-			
	Dark Current	< 0.001 e^-/pix/s			
	Spurious Count Rate	Small compared to dark current			
	Quantum Eff.	> 80% over bandwidth			
	Format	> 2k × 2k			
UV Single-photon Detectors for Enhanced Exoplanet Science	Bandwidth	200 nm – 400 nm	EBCMOS and MCP detectors need better quantum eff., and improvements in lifetime; MKID & TES detectors also apply here	2-4	Technology, Engineering, Manufacturing
	Read Noise	<< 1 e^-			
	Dark Current	< 0.001 e^-/pix/s			
	Spurious Count Rate	Small compared to dark current			
	Quantum Eff.	> 50% over bandwidth			
	Format	> 2k × 2k			
Large-Format High-Sensitivity UV Detectors for General Astrophysics	Bandwidth	90 nm – 300 nm	Same as above; δ-doped EMCCD also a candidate, but needs rad.-hard testing and lower clock-induced charge	4	Technology, Engineering, Manufacturing
	Read Noise	< 5 e^-			
	Quantum Eff.	> 70%			
	Format	> 2k × 2k			

Detectors



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TRL 5

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Visible-NIR Single-photon Detectors for Enabling Exoplanet Science

- Competitively-selected teams pursuing EMCCD, HgCdTe, superconducting techs, etc.
- Downselect to focus resources
- Final development of selected techs.

UV Single-photon Detectors for Enhanced Exoplanet Science

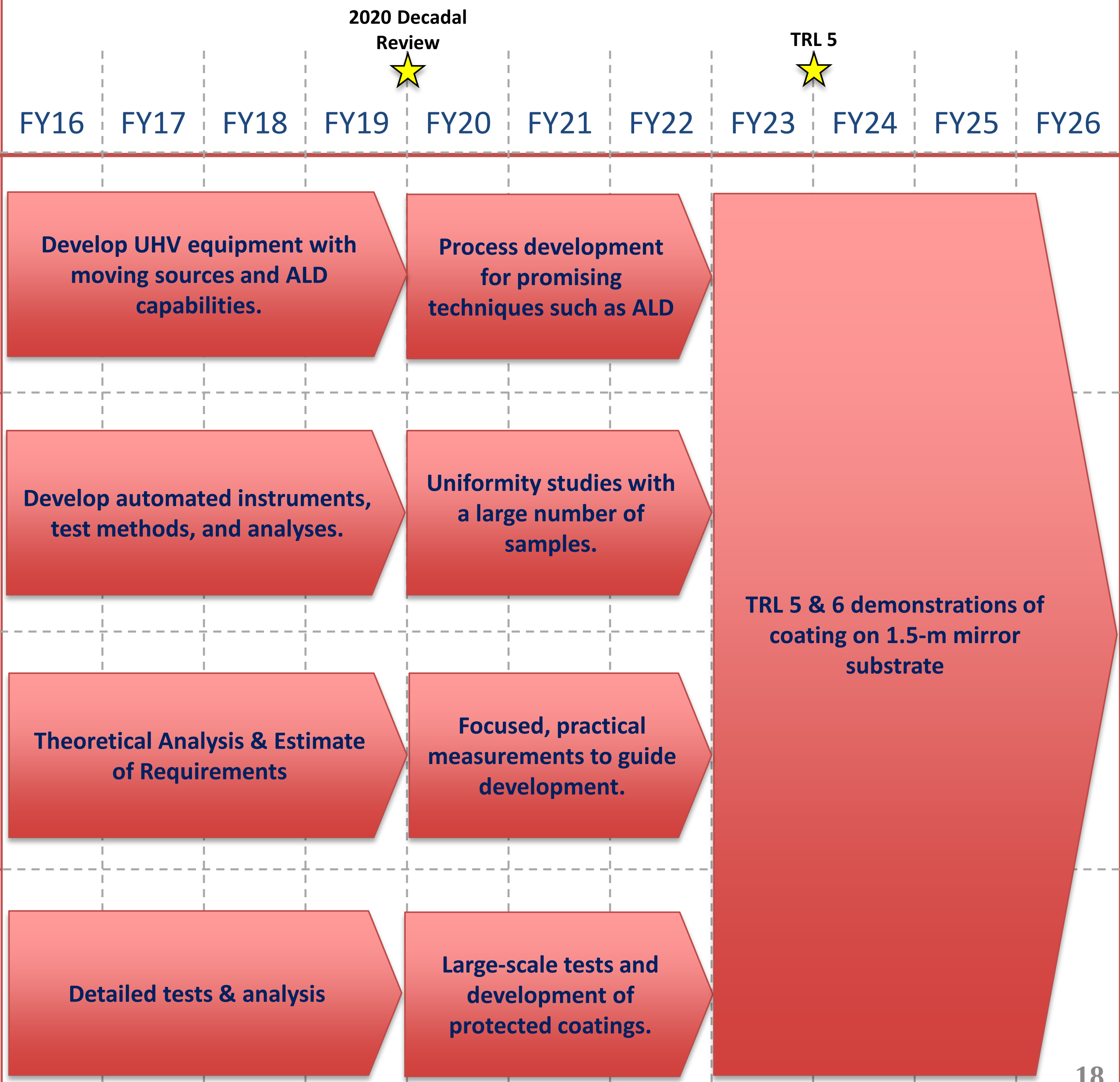
- Collaboration between NASA, Industry, Universities
  Pursue parallel detector technologies (EB-CMOS, MCP, etc.)
- Downselect to candidate detector & develop to TRL 6

Large-Format High-Sensitivity UV Detectors for General Astrophysics

- Radiation testing of EMCCDs first priority
- Recommend short-list of candidates to Decadal
- Flight-qualify; Develop to TRL 6

Mirror Coatings	**Parameter**	**Need**	**Capability**	**Current TRL**	**Technology, Engineering, or Manufacturing**
Reflectivity	90 nm – 120 nm	> 70%	< 50%	2	Technology, Engineering
	120 nm – 300 nm	> 90%	80%	3	
	> 300 nm	> 90%	> 90%	5	
Uniformity	90 nm – 120 nm	< 1%	TBD	2	Engineering, Manufacturing
	120 nm – 250 nm	< 1%	> 2%	3	
	> 250 nm	< 1%	1-2%	4	
Polarization	≥ 90 nm	< 1%	Not yet assessed; requires study	2	Technology
Durability	-	Stable performance over mission lifetime (10 years minimum)	Stable performance, but with limited starting reflectivity below 200 nm	4	Engineering, Manufacturing

Mirror Coatings



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Reflectivity

Develop UHV equipment with moving sources and ALD capabilities.

Process development for promising techniques such as ALD

Uniformity

Develop automated instruments, test methods, and analyses.

Uniformity studies with a large number of samples.

Polarization

Theoretical Analysis & Estimate of Requirements

Focused, practical measurements to guide development.

Durability

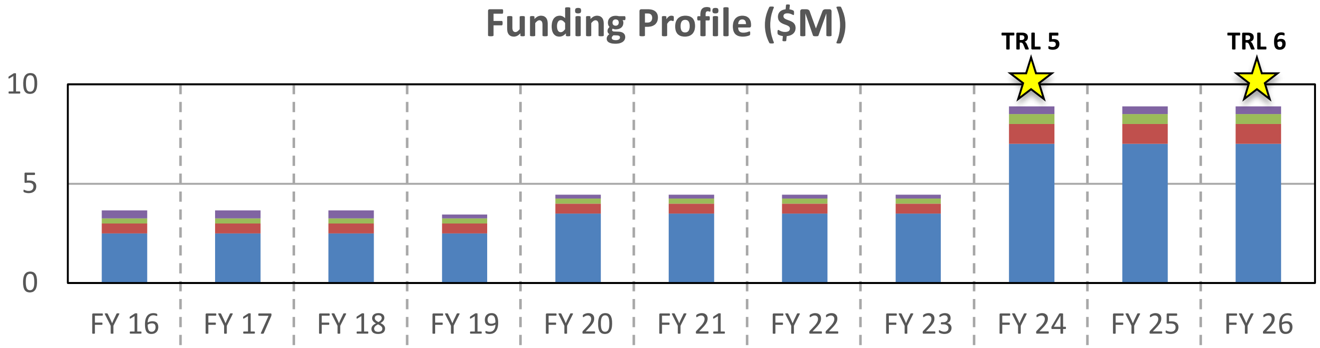
Detailed tests & analysis

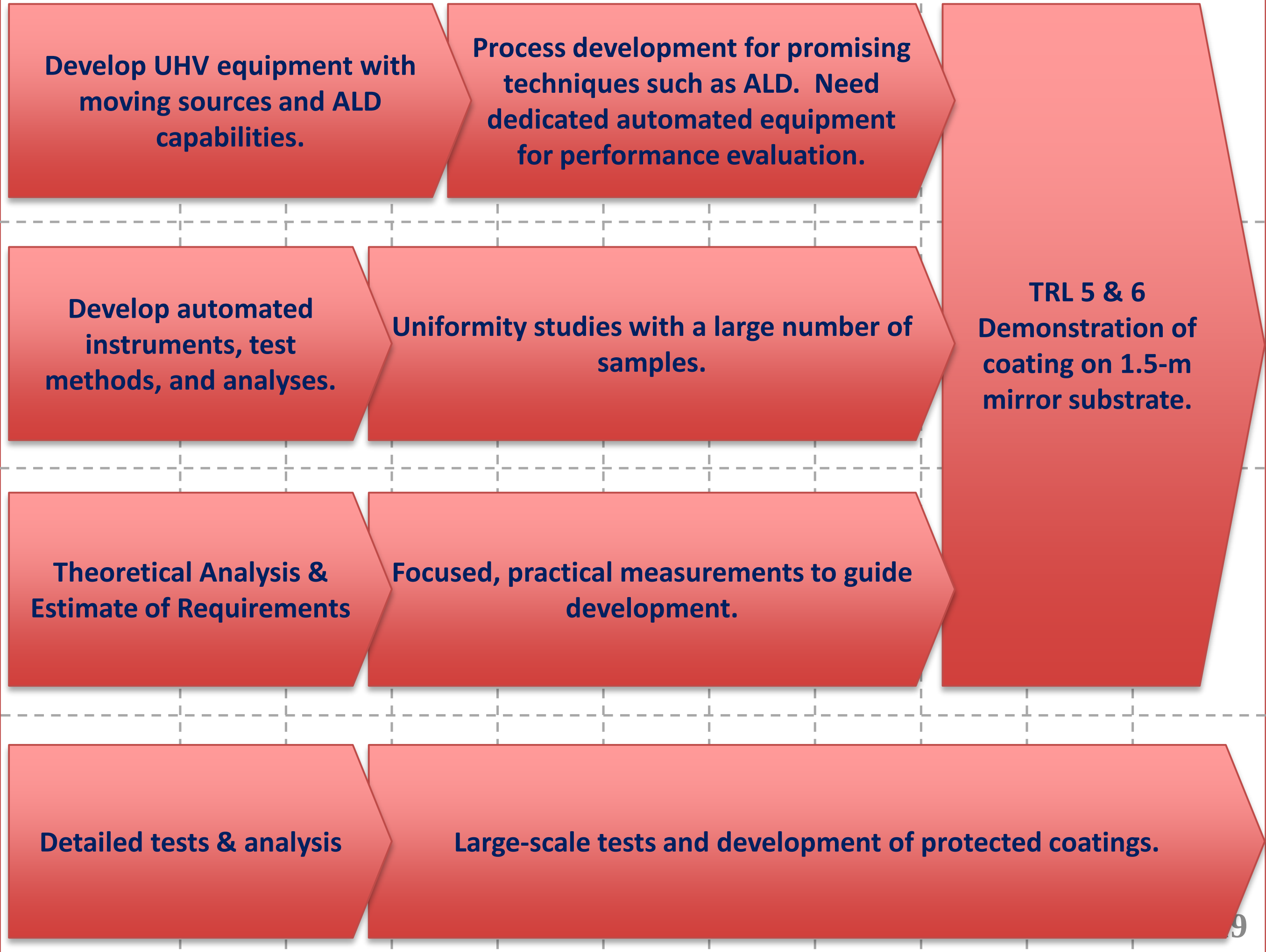
Large-scale tests and development of protected coatings.

TRL 5 & 6 demonstrations of coating on 1.5-m mirror substrate

Mirror Coatings

($32.2M)





UV Coating Reflectivity

- Develop UHV equipment with moving sources and ALD capabilities.
- Process development for promising techniques such as ALD. Need dedicated automated equipment for performance evaluation.

UV Coating Uniformity

- Develop automated instruments, test methods, and analyses.
- Uniformity studies with a large number of samples.

UV Coating Polarization

- Theoretical Analysis & Estimate of Requirements
- Focused, practical measurements to guide development.

TRL 5 & 6 Demonstration of coating on 1.5-m mirror substrate.

Coating Environmental Durability

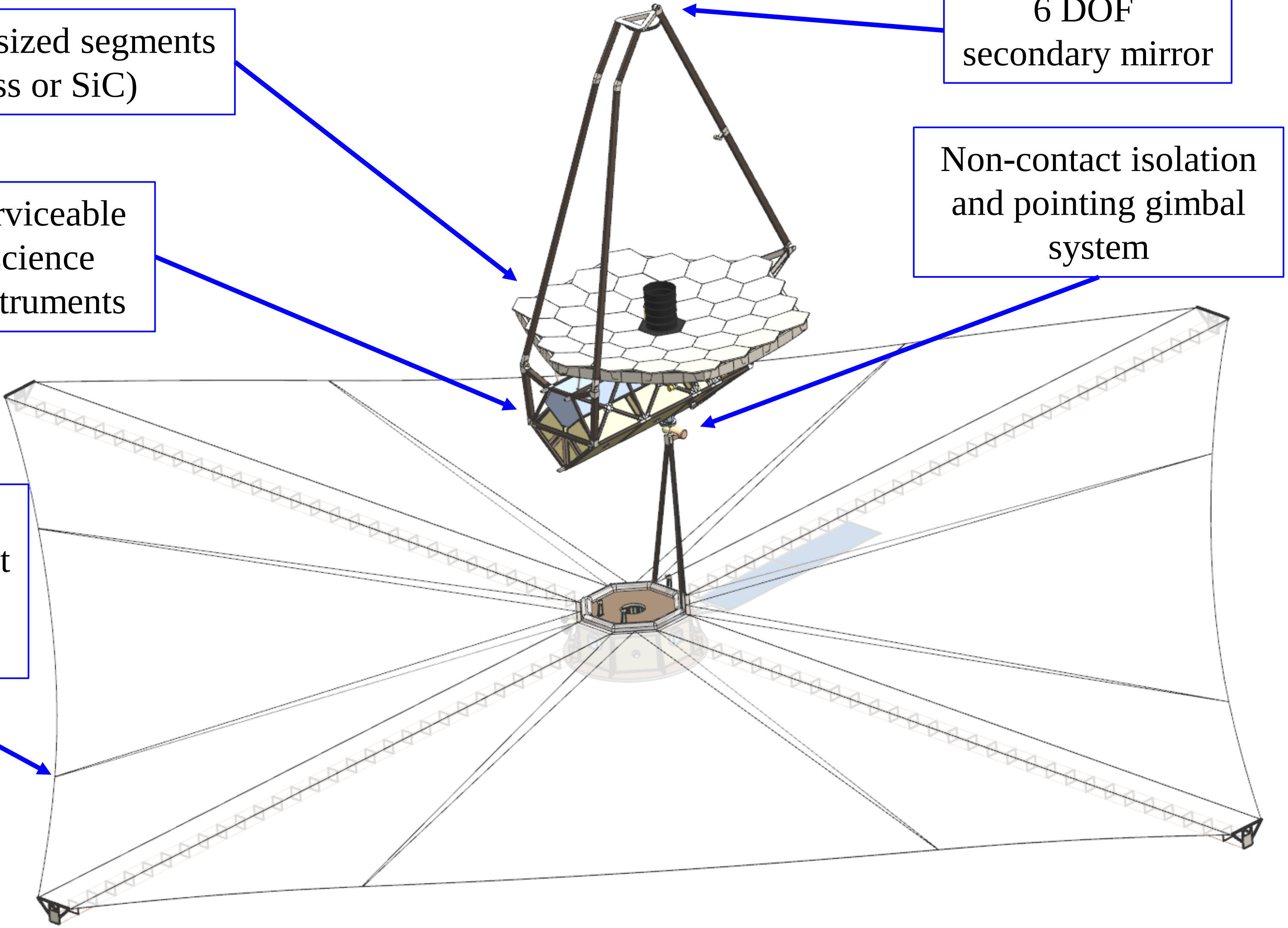
- Detailed tests & analysis
- Large-scale tests and development of protected coatings.

Conclusions

- A multi-institutional, studying a large UV-Optical-IR telescope with two science goals:
  - Detect and characterize habitable exoplanets
  - Broad array of general astrophysical observations
- Identified 5 key technologies to enable ATLAST
  - Internal Coronagraph
  - Starshade
  - Ultra-stable large-aperture telescopes
  - Detectors
  - Mirror Coatings
- Recommended actions for developing technologies to TRL 5 in time for a new mission start in 2024

BACKUP

ATLAST Segmented Architecture: At a Glance



36 JWST-sized segments (Glass or SiC)

6 DOF secondary mirror

Serviceable science instruments

Non-contact isolation and pointing gimbal system

Sunshield maintains constant sun-angle for thermal stability

Notional Instrument Requirements

Science Instrument	Parameter	Requirement	Stretch Goal
UV Multi-Object Spectrograph	Wavelength Range	100 nm – 300 nm	90 nm – 300 nm
	Field-of-View	1 – 2 arcmin	-
	Spectral Resolution	R = 20,000 – 300,000 (selectable)	-
Visible-NIR Wide-field Imager	Wavelength Range	300 nm – 1.8 µm	300 nm – 2.5 µm
	Field-of-View	4 – 8 arcmin	-
	Image Resolution	Nyquist sampled at 500 nm	-
Visible-NIR Integral Field Spectrograph	Wavelength Range	300 nm – 1.8 µm	300 nm – 2.5 µm
	Field-of-View	4 – 8 arcmin	-
	Spectral Resolution	R = 100 – 10,000 (selectable)	-
MIR Transit Spectrograph	Wavelength Range	Sensitivity to 5 µm	-
	Field-of-View	TBD	-
	Spectral Resolution	R = 200	-
Starlight Suppression System	Wavelength Range	400 nm – 1.8 µm	200 nm – 2.5 µm
	Raw Contrast	1×10^{-10}	-
	Contrast Stability	1×10^{-11} over integration	-
	Inner-working angle	36 milli-arcsec @ 1 µm	-
	Outer-working angle	> 0.5 arcsec @ 1 µm	-
Multi-Band Exoplanet Imager	Field-of-View	~0.5 arcsec	-
	Resolution	Nyquist sampled at 500 nm	-
Exoplanet Spectrograph	Field-of-View	~0.5 arcsec	-
	Resolution	R = 70 – 500 (selectable)	-