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

Presented by:
Matthew R. Bolcar
NASA Goddard Space Flight Center

ATLAST Technology Development Team:
What is ATLAST?

- Mission concept study for a large UV-Optical-Infrared space telescope (“LUVOIR”)
- Multiple engineering reference designs being explored by a multi-institutional team
- Similar in scope to AURA’s High Definition Space Telescope (HDST)
What is ATLAST?

• “ATLAST”, “LUVOIR”, “HDST” are all *mostly* interchangeable

• **LUVOIR**: defined in NASA Astrophysics 30-year roadmap
  – Architecture is non-specific

• **HDST**: see:
  – Advocates for a large segmented aperture

• **ATLAST**: multiple architectures being considered
  – Has engineering reference designs for segmented and monolithic systems

• All have very similar science goals
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

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

• Assume a new mission start circa 2024
  – Technologies must be TRL 5 by this time
  – 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 conservatively and refine as technologies develop and modeling is performed
Technologies
Internal Coronagraph

- Instrument internal to the observatory that suppresses the on-axis starlight

- Nimble: allows the observation of many planetary systems in a fixed mission lifetime
  - Dozens of exoEarths predicted with reasonable assumptions\(^1\)

- Impose stringent wavefront stability requirements on the telescope

- Limited inner-working angle at long wavelengths
  - Difficult to observe some biosignature spectral features in the NIR

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Need</th>
<th>Capability</th>
<th>Current TRL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw Contrast</td>
<td>$1 \times 10^{-10}$ (detect) $5 \times 10^{-10}$ (char.)</td>
<td>$3.2 \times 10^{-10}$</td>
<td></td>
</tr>
<tr>
<td>IWA</td>
<td>$3.6 \lambda/D$ (detect) $2.0 \lambda/D$ (char.)</td>
<td>$3 \lambda/D$</td>
<td></td>
</tr>
<tr>
<td>OWA</td>
<td>$\sim 64 \lambda/D$</td>
<td>$16 \lambda/D$</td>
<td>3</td>
</tr>
<tr>
<td>Bandpass</td>
<td>10-20% (instantaneous) $400$ nm – 1.8 $\mu$m (total) $200$ nm – 2.5 $\mu$m (goal)</td>
<td>10%</td>
<td></td>
</tr>
<tr>
<td>Aperture</td>
<td>Obscured, segmented</td>
<td>Unobscured</td>
<td></td>
</tr>
<tr>
<td>WFSC</td>
<td>Fast, low-order, at stellar photon rates</td>
<td>Slow, tip/tilt, bright lab source</td>
<td></td>
</tr>
<tr>
<td>Actuator count</td>
<td>128$\times$128 (continuous) $&gt;3000$ (segmented)</td>
<td>64$\times$64 (continuous) $&lt;200$ (segmented)</td>
<td>3</td>
</tr>
<tr>
<td>Environmental</td>
<td>Robust, rad. hard</td>
<td>Testing underway</td>
<td></td>
</tr>
<tr>
<td>Electronics</td>
<td>$&gt;16$ bits, high-throughput</td>
<td>$\sim 16$ bit, dense cabling</td>
<td></td>
</tr>
<tr>
<td>Bandwidth</td>
<td>Closed-loop $&gt; a$ few Hz</td>
<td>Human-in-the-loop</td>
<td>3</td>
</tr>
<tr>
<td>Electronics</td>
<td>Rad. hard, $&gt;100$ GFLOPS/W</td>
<td>$&lt;20$ GFLOPS/W</td>
<td></td>
</tr>
<tr>
<td>PSF Calibration</td>
<td>Factor of 50-100× improvement in contrast</td>
<td>25× demonstrated 30× goal for WFIRST</td>
<td>3</td>
</tr>
</tbody>
</table>
Starshade

- Separate spacecraft that flies in formation with telescope to block incoming starlight

- Not nimble: long slew times between observations limits the exoplanet yield for a fixed mission lifetime

- No special requirements imposed on telescope

- Inner working angle is independent of wavelength or telescope diameter
<table>
<thead>
<tr>
<th>Starshade</th>
<th>Parameter</th>
<th>Need</th>
<th>Capability</th>
<th>Current TRL</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Starshade Construction and Deployment</strong></td>
<td>-</td>
<td>Petal and central truss design consistent with an 80-m class starshade</td>
<td>Demonstrated prototype petal for 40-m class starshade</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Demonstrate manufacturing and deployment tolerances</td>
<td>Demonstrated deployment tolerances with a 12-m Astromesh antenna with 4 petals</td>
<td></td>
</tr>
<tr>
<td><strong>Optical Edges</strong></td>
<td>Edge radius</td>
<td>≤ 1 μm</td>
<td>≥ 10 μm</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Reflectivity</td>
<td>≤ 10%</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Stowed radius</td>
<td>≤ 1.5 m</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td><strong>Formation Flight</strong></td>
<td>Lateral sensing error</td>
<td>≤ 20 cm</td>
<td>-</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Peak-to-peak control</td>
<td>&lt; 1 m</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Centroid estimation</td>
<td>≤ 0.3% of optical resolution</td>
<td>≥ 1%</td>
<td></td>
</tr>
<tr>
<td><strong>Contrast Performance Demonstration and Model Validation</strong></td>
<td>-</td>
<td>1×10⁻¹⁰ broadband contrast at Fresnel numbers ≤ 50</td>
<td>3×10⁻¹⁰ contrast, excluding petal edges, narrowband, at Fresnel number of ~500</td>
<td>3</td>
</tr>
<tr>
<td><strong>Starshade Propulsion &amp; Refueling</strong></td>
<td>-</td>
<td>Propulsion &amp; refueling to enable &gt; 500 slews during 3 years of a 5-year mission</td>
<td>Requires study; robotic refueling appears feasible</td>
<td>3</td>
</tr>
</tbody>
</table>
Ultra-stable Large Aperture Telescopes

• Provide wavefront stability for an internal coronagraph

• Incorporates entire optical system:
  – Mirrors
  – Structure
  – Thermal control system
  – Vibration isolation system
  – Metrology & Actuators
<table>
<thead>
<tr>
<th><strong>Ultra-stable Large Aperture Telescopes</strong></th>
<th><strong>Parameter</strong></th>
<th><strong>Need</strong></th>
<th><strong>Capability</strong></th>
<th><strong>Current TRL</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mirrors</strong></td>
<td>Areal Density</td>
<td>&lt; 36 kg/m² (Delta IVH) &lt; 500 kg/m² (SLS)</td>
<td>~12 kg/m² (SiC) ~35 kg/m² (ULE) ~70 kg/m² (JWST)</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Areal Cost</td>
<td>&lt; $2 M/m²</td>
<td>~$6 M/m² (JWST)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Areal Production Rate</td>
<td>30-50 m²/year</td>
<td>~4 m²/year (JWST) ~1 m²/year (HST) ~100-300 m²/year planned by TMT but not yet demonstrated</td>
<td>4</td>
</tr>
<tr>
<td><strong>Stable Structures</strong></td>
<td>Moisture Expansion</td>
<td>Zero after initial moisture release</td>
<td>Continuous moisture release</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Lurch</td>
<td>&lt; 10 pm / wavefront control step</td>
<td>Micro-lurch at joint interfaces</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Metrology</td>
<td>High-speed picometer metrology to validate performance</td>
<td>Nanometer speckle interferometry on JWST</td>
<td>4</td>
</tr>
<tr>
<td><strong>Thermal Stability</strong></td>
<td>Material Stability</td>
<td>~10 nm/K</td>
<td>~100 nm/K</td>
<td>3</td>
</tr>
<tr>
<td><strong>Disturbance Isolation System</strong></td>
<td>End-to-end Attenuation</td>
<td>140 dB at frequencies &gt; 20 Hz</td>
<td>80 dB at frequencies &gt; 40 Hz (JWST passive isolator only)</td>
<td>4</td>
</tr>
<tr>
<td><strong>Metrology &amp; Actuators</strong></td>
<td>Sensing Accuracy</td>
<td>~1 pm</td>
<td>~1 nm</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Control Accuracy</td>
<td>~1 pm</td>
<td>~5 nm</td>
<td>4</td>
</tr>
</tbody>
</table>
Detectors

- Need improvements to enable and enhance exoplanet science

- Better UV science enabled by improvements in sensitivity and format

See: B. Rauscher, “Detector requirements for coronagraphic biosignature characterization”, paper 9602-12
<table>
<thead>
<tr>
<th>Detectors</th>
<th>Parameter</th>
<th>Need</th>
<th>Capability</th>
<th>Current TRL</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Visible-NIR Single-photon Detectors for Enabling Exoplanet Science</strong></td>
<td>Bandwidth</td>
<td>400 nm – 1.8 µm (2.5 µm goal)</td>
<td>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 &amp; TES meet requirements but require cryo ops.</td>
<td>3-5</td>
</tr>
<tr>
<td></td>
<td>Read Noise</td>
<td>&lt;&lt; 1 e⁻</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dark Current</td>
<td>&lt; 0.001 e⁻/pix/s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Spurious Count Rate</td>
<td>Small compared to dark current</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Quantum Eff.</td>
<td>&gt; 80% over bandwidth</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Format</td>
<td>&gt; 2k × 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>UV Single-photon Detectors for Enhanced Exoplanet Science</strong></td>
<td>Bandwidth</td>
<td>200 nm – 400 nm</td>
<td>EBCMOS and MCP detectors need better quantum eff., and improvements in lifetime; MKID &amp; TES detectors also apply here</td>
<td>2-4</td>
</tr>
<tr>
<td></td>
<td>Read Noise</td>
<td>&lt;&lt; 1 e⁻</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dark Current</td>
<td>&lt; 0.001 e⁻/pix/s</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Spurious Count Rate</td>
<td>Small compared to dark current</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Quantum Eff.</td>
<td>&gt; 50% over bandwidth</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Format</td>
<td>&gt; 2k × 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Large-Format High-Sensitivity UV Detectors for General Astrophysics</strong></td>
<td>Bandwidth</td>
<td>90 nm – 300 nm</td>
<td>Same as above; δ-doped EMCCD also a candidate, but needs rad.-hard testing and lower clock-induced charge</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Read Noise</td>
<td>&lt; 5 e⁻</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Quantum Eff.</td>
<td>&gt; 70%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Format</td>
<td>&gt; 2k × 2</td>
<td></td>
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</tbody>
</table>
Mirror Coatings

• Needed for Primary & Secondary mirror surfaces

• Broadband performance from UV to NIR

• Compatible with high-contrast imaging by internal coronagraph

## Mirror Coatings

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Need</th>
<th>Capability</th>
<th>Current TRL</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Reflectivity</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>90 nm – 120 nm</td>
<td>&gt; 70%</td>
<td>&lt; 50%</td>
<td>2</td>
</tr>
<tr>
<td>120 nm – 300 nm</td>
<td>&gt; 90%</td>
<td>80%</td>
<td>3</td>
</tr>
<tr>
<td>&gt; 300 nm</td>
<td>&gt; 90%</td>
<td>&gt; 90%</td>
<td>5</td>
</tr>
<tr>
<td><strong>Uniformity</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>90 nm – 120 nm</td>
<td>&lt; 1%</td>
<td>TBD</td>
<td>2</td>
</tr>
<tr>
<td>120 nm – 250 nm</td>
<td>&lt; 1%</td>
<td>&gt; 2%</td>
<td>3</td>
</tr>
<tr>
<td>&gt; 250 nm</td>
<td>&lt; 1%</td>
<td>1-2%</td>
<td>4</td>
</tr>
<tr>
<td><strong>Polarization</strong></td>
<td></td>
<td>&lt; 1%</td>
<td></td>
</tr>
<tr>
<td>≥ 90 nm</td>
<td></td>
<td>Not yet assessed; requires study</td>
<td>2</td>
</tr>
<tr>
<td><strong>Durability</strong></td>
<td></td>
<td>Stable performance over mission lifetime (10 years minimum)</td>
<td></td>
</tr>
<tr>
<td>-</td>
<td></td>
<td>Stable performance, but with limited starting reflectivity below 200 nm</td>
<td>4</td>
</tr>
<tr>
<td>Development Activities</td>
<td>FY16</td>
<td>FY17</td>
<td>FY18</td>
</tr>
<tr>
<td>------------------------</td>
<td>------</td>
<td>------</td>
<td>------</td>
</tr>
<tr>
<td><strong>Internal Coronagraph</strong></td>
<td><img src="image" alt="2020 Decadal Review" /></td>
<td><img src="image" alt="TRL 5" /></td>
<td><strong>Leverage WFIRST/AFTA Investment Fund Development of new promising techniques</strong></td>
</tr>
<tr>
<td>Starshade</td>
<td>Continue investments in truss, formation flight, edge techs. Close on model validation tests</td>
<td><img src="image" alt="FY20" /></td>
<td><img src="image" alt="FY22" /></td>
</tr>
<tr>
<td><strong>Ultra-stable Large Aperture Telescopes</strong></td>
<td><img src="image" alt="FY20" /></td>
<td><img src="image" alt="FY22" /></td>
<td><img src="image" alt="FY21" /></td>
</tr>
<tr>
<td>Separate subscale demonstrations of structures &amp; disturbance isolation AMSD-like mirror development program</td>
<td><img src="image" alt="FY20" /></td>
<td><img src="image" alt="FY22" /></td>
<td><img src="image" alt="FY21" /></td>
</tr>
<tr>
<td><strong>Detectors</strong></td>
<td><img src="image" alt="FY20" /></td>
<td><img src="image" alt="FY22" /></td>
<td><img src="image" alt="FY21" /></td>
</tr>
<tr>
<td>Radiation test promising EMCCD techs. NASA/industry.academia collaborate on parallel techs.</td>
<td><img src="image" alt="FY20" /></td>
<td><img src="image" alt="FY22" /></td>
<td><img src="image" alt="FY21" /></td>
</tr>
<tr>
<td><strong>Mirror Coatings</strong></td>
<td><img src="image" alt="FY20" /></td>
<td><img src="image" alt="FY22" /></td>
<td><img src="image" alt="FY21" /></td>
</tr>
</tbody>
</table>
| Individually develop reflectivity, uniformity, polarization, durability performance on small scale samples | ![FY20](image) | ![FY22](image) | ![FY21](image) | ![FY23](image) | ![FY25](image) | ![FY24](image) | ![FY26](image) | ![FY27](image) | ![FY28](image) | ![FY29](image) | ![FY30](image) | **Final environmental and radiation qualification of selected technologies** | **Full scale coating demonstration on 1.5-m class mirror; Scaleable to larger mirrors in event monolithic architecture is baselined**
Conclusions

• A multi-institutional team, 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
Questions?
BACKUP
Historical Context

• 2009
  – Multi-institutional team studies ATLAST concept; 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
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

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

<table>
<thead>
<tr>
<th>Year</th>
<th>Task</th>
</tr>
</thead>
<tbody>
<tr>
<td>FY16</td>
<td>Multi-institution study of new &amp; existing coronagraph techniques</td>
</tr>
<tr>
<td>FY17</td>
<td>Development of top 3-4 candidates to TRL 4</td>
</tr>
<tr>
<td>FY18</td>
<td>Downselect to ~2 candidates; Develop to TRL 5</td>
</tr>
<tr>
<td>FY19</td>
<td>Select mission primary and backup; Develop to TRL 6</td>
</tr>
<tr>
<td>FY20</td>
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<tr>
<td>FY21</td>
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<td>FY22</td>
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<td>FY24</td>
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<tr>
<td>FY25</td>
<td></td>
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<tr>
<td>FY26</td>
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</tbody>
</table>

**TRL 5**

- Select mission primary and backup; Develop to TRL 6

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### Broadband High-Contrast Coronagraph

- includes Wavefront Sensing & Control (WFSC)
- Leverage WFIRST/AFTA investment in WFSC

### Deformable Mirrors

- Industry Engagement; Improve actuator counts, yield, electronics precision
- Leverage WFIRST/AFTA investment
- Select Mirror Arch.

### 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 50-100x in contrast improvement

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**2020 Decadal Review**

- **TRL 5**

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**9602-8**
<table>
<thead>
<tr>
<th><strong>Starshade</strong></th>
<th><strong>2020 Decadal Review</strong></th>
<th><strong>TRL 5</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Starshade Construction and Deployment</td>
<td>FY16</td>
<td>FY17</td>
</tr>
<tr>
<td>Develop and demonstrate fabrication of prototype 80-meter class petals &amp; truss</td>
<td></td>
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<tr>
<td>Demonstrate deployment of truss and petals to flight tolerances</td>
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<tr>
<td>Environmental qualification of materials, mechanisms, etc.</td>
<td></td>
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<tr>
<td>Optical Edges</td>
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<tr>
<td>Leverage ongoing investments in starshade material technology development</td>
<td></td>
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<tr>
<td>Formation Flight</td>
<td></td>
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<tr>
<td>Continue investments in formation flight</td>
<td></td>
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<tr>
<td>Contrast Performance Demonstration and Model Validation</td>
<td></td>
<td></td>
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<tr>
<td>Continue investments in model validation and laboratory demonstrations of scale-designs</td>
<td></td>
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<tr>
<td>Starshade Propulsion &amp; Refueling</td>
<td></td>
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<tr>
<td>Investigate servicing and propulsion needs for enhanced starshade lifetime and slew rate</td>
<td></td>
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<tr>
<td>Engage human/robotic servicing community to develop infrastructure</td>
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</tbody>
</table>

9602-8
# Ultra-stable Large Aperture Telescopes

<table>
<thead>
<tr>
<th>Mirrors</th>
<th>Advanced Mirror System Demonstrator (AMSD)-like program comparing materials &amp; architectures</th>
<th>Downselect to ~4 candidates</th>
<th>Downselect to 2 candidates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stable Structures</td>
<td>Demonstration of subscale (segment-level) structure system dynamics</td>
<td>Expand to multi-segment/larger scale;</td>
<td>Incorporate thermal control and dynamic isolation system;</td>
</tr>
<tr>
<td>Thermal Stability</td>
<td>(Investigate as part of Mirrors and Stable Structures efforts)</td>
<td></td>
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<tr>
<td>Disturbance Isolation System</td>
<td>Invest in high-TRL testbed demonstrations; Study low-TRL options for risk reduction</td>
<td></td>
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<tr>
<td>Metrology &amp; Actuators</td>
<td>Engage industry for improved metrology techniques and actuators</td>
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</tr>
</tbody>
</table>

2020 Decadal Review

TRL 5

Subscale stability testbed:

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

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**

<table>
<thead>
<tr>
<th>Reflectivity</th>
<th>FY16</th>
<th>FY17</th>
<th>FY18</th>
<th>FY19</th>
<th>FY20</th>
<th>FY21</th>
<th>FY22</th>
<th>FY23</th>
<th>FY24</th>
<th>FY25</th>
<th>FY26</th>
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</thead>
<tbody>
<tr>
<td>Develop UHV equipment with moving sources and ALD capabilities.</td>
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<tr>
<td>Process development for promising techniques such as ALD</td>
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<table>
<thead>
<tr>
<th>Uniformity</th>
<th>FY16</th>
<th>FY17</th>
<th>FY18</th>
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<th>FY23</th>
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<th>FY25</th>
<th>FY26</th>
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</thead>
<tbody>
<tr>
<td>Develop automated instruments, test methods, and analyses.</td>
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<tr>
<td>Uniformity studies with a large number of samples</td>
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<thead>
<tr>
<th>Polarization</th>
<th>FY16</th>
<th>FY17</th>
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<th>FY24</th>
<th>FY25</th>
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<tbody>
<tr>
<td>Theoretical Analysis &amp; Estimate of Requirements</td>
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<tr>
<td>Focused, practical measurements to guide development</td>
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<table>
<thead>
<tr>
<th>Durability</th>
<th>FY16</th>
<th>FY17</th>
<th>FY18</th>
<th>FY19</th>
<th>FY20</th>
<th>FY21</th>
<th>FY22</th>
<th>FY23</th>
<th>FY24</th>
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</thead>
<tbody>
<tr>
<td>Detailed tests &amp; analysis</td>
<td></td>
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<tr>
<td>Large-scale tests and development of protected coatings</td>
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</tbody>
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2020 Decadal Review

TRL 5

Large-scale tests and development of protected coatings

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

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