# Technology Development for the Advanced Technology Large Aperture Space Telescope (ATLAST)

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

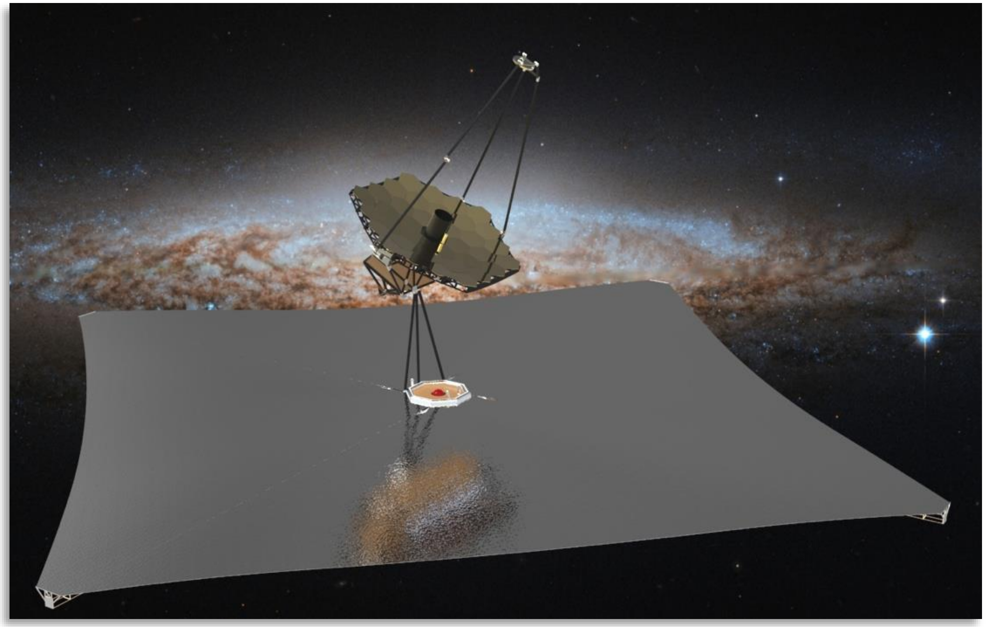
**ATLAST Technology Development Team:**
M. R. Bolcar, K. Balasubramanian, M. Clampin, J. Crooke, L. Feinberg, M. Postman, M. Quijada, B. J. Rauscher, D. Redding, S. Shaklan, H. P. Stahl, C. Stahle, H. Thronson

# What is ATLAST?

- Mission concept study for a large space telescope operating in the UV-Optical-Infrared band

- Multiple engineering reference designs being explored by a multi-institutional team
  - 9.2-m Scaleable Segmented, 8-m Monolith, etc.

- Similar in scope to AURA's High Definition Space Telescope (HDST)



# ATLAST Science

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

- Perform a broad array of UVOIR general astrophysics:
  - Galaxy, star, and planet formation and evolution
  - Flow of material between galaxies
  - Observations within our own solar system: planets, satellites, comets, asteroids, Kuiper Belt objects, etc.

- 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 | - | - |

*No requirements levied on telescope beyond the 1.8 requirement/2.5+ μm goal.

# 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

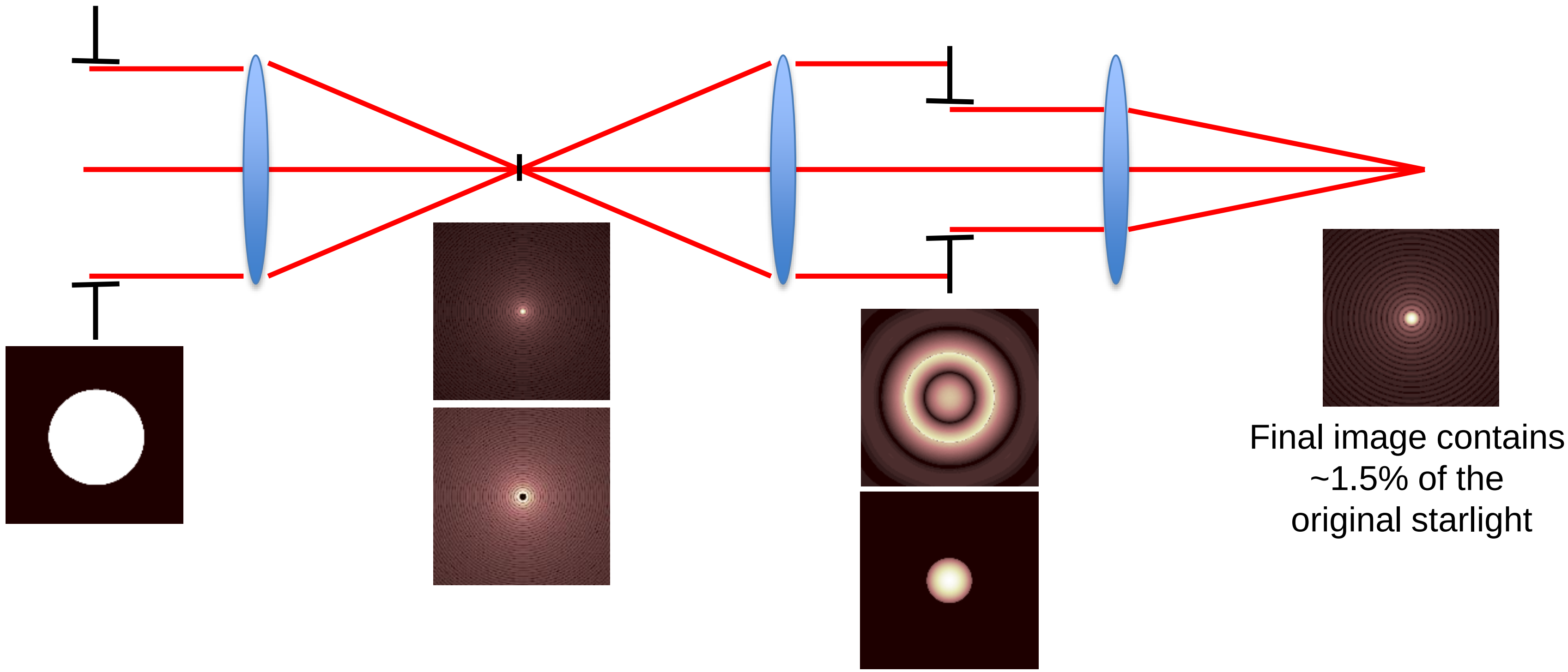
# Assumptions

- Assume a new mission start in the mid-2020's
  - Technologies must be TRL 6 by Preliminary Design Review (PDR)
  - Technology development plan must be credible in time for 2020 Decadal Survey
- Assume flexibility with respect to architecture
  - ATLAST team studied a limited set of design concepts; the technology plan takes a broader perspective
  - i.e. develop for both monolithic and segmented apertures, develop both internal coronagraphs and starshades, etc.
- Adopt a conservative approach in identifying gaps
  - This is 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 dozens of exoEarths in a fixed mission lifetime[1]
  - Imposes stringent wavefront stability requirements on the telescope
  - Limited inner-working angle at longer wavelengths

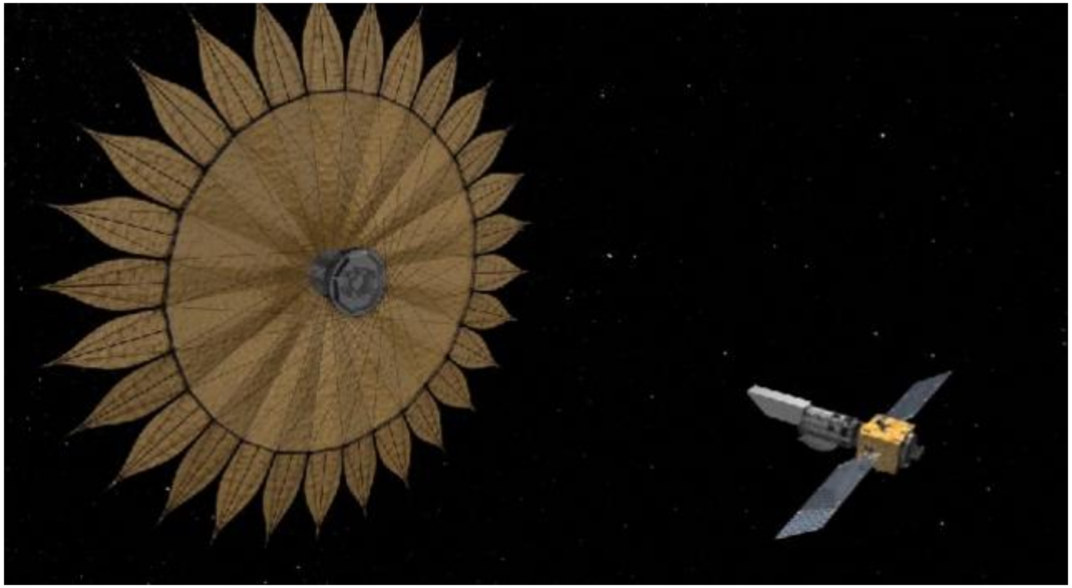



[1]Stark, *et al.*, "Maximizing the ExoEarth Candidate Yield from a Future Direct Imaging Mission", *ApJ*, **795** (2014)

| Internal Coronagraph | Parameter | Need | Capability | Current TRL |
|---|---|---|---|---|
| Broadband High-Contrast Coronagraph<br><br>includes Wavefront Sensing & Control (WFSC) | Raw Contrast | $1\times10^{-10}$ (detect)<br>$5\times10^{-10}$ (char.) | $3.2\times10^{-10}$ | 3 |
| | IWA | 3.6 $\lambda$/D (detect)<br>2.0 $\lambda$/D (char.) | 3 $\lambda$/D | |
| | OWA | ~ 64 $\lambda$/D | 16 $\lambda$/D | |
| | Bandpass | 10-20% (instantaneous)<br>400 nm – 1.8 μm (total)<br>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)<br>>3000 (segmented) | 64×64 (continuous)<br><200 (segmented) | 3 |
| | 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 |
| | Electronics | Rad. hard, >100 GFLOPS/W | <20 GFLOPS/W | |
| Starlight Suppression Image Processing | PSF Calibration | Factor of 50-100× improvement in contrast | 25× demonstrated<br>30× goal for WFIRST | 3 |

# 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



| Starshade | Parameter | Need | Capability | Current TRL |
|---|---|---|---|---|
| Starshade Construction and Deployment | - | Petal and central truss design consistent with an 80-m class starshade<br><br>Demonstrate manufacturing and deployment tolerances | Demonstrated prototype petal for 40-m class starshade<br><br>Demonstrated deployment tolerances with a 12-m Astromesh antenna with 4 petals | 3 |
| Optical Edges | Edge radius | ≤ 1 μm | ≥ 10 μm | 3 |
| | Reflectivity | ≤ 10% | - | |
| | Stowed radius | ≤ 1.5 m | - | |
| Formation Flight | Lateral sensing error | ≤ 20 cm | ≤ 1 m | 3 |
| | Peak-to-peak control | < 1 m | - | |
| | Centroid estimation | ≤ 0.3% of optical resolution | ≥ 1% | |
| Contrast Performance Demonstration and Model Validation | - | $1\times10^{-10}$ broadband contrast at Fresnel numbers ≤ 50 | $4\times10^{-10}$ contrast, excluding petal edges, narrowband, at Fresnel number of ~100 | 3 |
| Starshade Propulsion & Refueling | - | Propulsion & refueling to enable > 500 slews during 3 years of a 5-year mission | Requires study; robotic refueling appears feasible | 3 |

# 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

| Ultra-stable Large Aperture Telescopes | Parameter | Need | Capability | Current TRL |
|---|---|---|---|---|
| Mirrors | Areal Density | < 36 kg/m$^2$ (Delta IVH)<br>< 500 kg/m$^2$ (SLS) | ~12 kg/m$^2$ (SiC)<br>~35 kg/m$^2$ (ULE)<br>~70 kg/m$^2$ (JWST) | 4 |
| | Areal Cost | < \$2 M/m$^2$ | ~\$6 M/m$^2$ (JWST) | |
| | Areal Production Rate | 30-50 m$^2$/year | ~4 m$^2$/year (JWST)<br>~1 m$^2$/year (HST)<br>~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 |
| | 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 |
| Disturbance Isolation System | End-to-end Attenuation | 140 dB at frequencies > 20 Hz | 80 dB at frequencies > 40 Hz (JWST passive isolator only) | 4 |
| Metrology & Actuators | Sensing Accuracy | ~1 pm | ~1 nm | 4 |
| | Control Accuracy | ~1 pm | ~5 nm | |

# Detectors

- Need improvements to enable and enhance exoplanet science
  - Improved sensitivity, lower noise

- Better UV science enabled by improvements in sensitivity and format

| Detectors | Parameter | Need | Capability | Current TRL |
| --- | --- | --- | --- | --- |
| Visible-NIR Single-photon Detectors for Enabling Exoplanet Science | Bandwidth | 400 nm – 1.8 μm (2.5 μm goal, sensitivity to 5 μm) | 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 |
| | 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;<br><br>MKID & TES detectors also apply here | 2-4 |
| | 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;<br><br>δ-doped EMCCD also a candidate, but needs rad.-hard testing and lower clock-induced charge | 4 |
| | Read Noise | < 5 $e^-$ | | |
| | Quantum Eff. | > 70% | | |
| | Format | > 2k × 2k | | |

# Mirror Coatings

- Needed for Primary & Secondary mirror surfaces

- Broadband performance from UV to NIR

- Compatible with high-contrast imaging by internal coronagraph

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

# Technology Development Activities:

- WFIRST coronagraph development milestones relevant to ATLAST:
  - Low-order WFSC (LOWFS) subsystem development towards 0.4 mas RMS pointing (9/30/15)
  - Detector electronics development towards < 0.001 $e^-$/pix/s dark current and < 1 $e^-$/pix/frame (8/25/16)
  - PIAACMC mask development and demonstration towards $10^{-8}$ contrast over 10% bandpass (9/30/16)
  - Contrast demonstration in a simulated dynamic environment (9/30/16)

# Technology Development Activities (cont.):

- New & ongoing SAT TDEM (coronagraph, starshade, DM)
  - Achromatic VNC Technology Maturation (Lyon/GSFC)
  - Segmented aperture nulling coronagraphy (Lyon/GSFC)
  - Next Generation VNC (Bolcar/GSFC)
  - Starshade straylight/edge scatter modeling & materials development (Casement/NGAS)
  - Field demonstration of starshade starlight suppression (Glassman/NGAS)
  - Optical & mechanical verification of external occulter (Kasdin/Princeton)
  - Formation flying for external occulters (Kasdin/Princeton)
  - Development of formation flying sensors (Cash/U. of Colorado, Boulder)
  - Optical shield for starshade inner disk subsystem (Thompson/JPL)
  - MEMS DM Development for space-based exoplanet detection (Bierden/Boston MMC)
  - Environmental testing of MEMS DMs (Helmbrecht/IrisAO)

# Technology Development Activities (cont.):

- New & ongoing SAT TCOR (coatings, detectors, mirrors):
  - UV Coatings, Materials and Processes (Bala/JPL)
  - Plasma enhanced ALD for FUV interference filters (Scowen/ASU)
  - High-efficiency detectors in photon-counting and large FPAs (Nikzad/JPL)
  - Advanced FUV/UV/Visible photon-counting ultralow-noise detectors (Nikzad/JPL)
  - Development of large-area photon-counting UV detectors (Vallerga/Berkely)
  - Advanced Mirror Technology Development Phase 2 (Stahl/MSFC)

# Technology Development Activities (cont.):

- Other:
  - Segmented aperture coronagraphy assessment (Shaklan/JPL, ExEp Program Office)

<table>
<tr><th rowspan="2">Development Activities</th><th></th><th></th><th></th><th colspan="2">2020 Decadal Review ☆</th><th></th><th></th><th colspan="2">TRL 5 ☆</th><th></th><th></th></tr>
<tr><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></tr>
<tr><td>Internal Coronagraph</td><td colspan="3">Leverage WFIRST/AFTA Investment<br>Fund Development of new promising techniques</td><td colspan="2">Develop top 3-4 candidates to TRL 4</td><td colspan="3">Downselect top 2 candidates<br>Incorporate DM and WFSC technology</td><td colspan="3">Select flight primary and backup<br>Develop to TRL 6</td></tr>
<tr><td>Starshade</td><td colspan="4">Continue investments in truss, formation flight, edge techs.<br>Close on model validation tests</td><td colspan="4">Demonstrate deployment of 80-m class truss & petals<br>Engage human/robotic servicing community</td><td colspan="3">Environmental testing of structure, blankets, edges, etc.</td></tr>
<tr><td>Ultra-stable Large Aperture Telescopes</td><td colspan="4">Separate subscale demonstrations of structures & disturbance isolation<br>AMSD-like mirror development program</td><td colspan="4">Combine structure, thermal, and dynamic systems; demonstrate stability<br>Select 2 candidate mirror techs.</td><td colspan="3">Subscale stability demonstration testbed integrates all components</td></tr>
<tr><td>Detectors</td><td colspan="4">Radiation test promising EMCCD techs.<br>NASA/industry/academia collaborate on parallel techs.</td><td colspan="4">Downselect promising technologies to focus resources</td><td colspan="3">Final environmental and radiation qualification of selected technologies</td></tr>
<tr><td>Mirror Coatings</td><td colspan="6">Individually develop reflectivity, uniformity, polarization, durability performance on small scale samples</td><td colspan="5">Full scale coating demonstration on 1.5-m class mirror; Scaleable to larger mirrors in event monolithic architecture is baselined</td></tr>
</table>

# Conclusions

- Multi-institutional ATLAST 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
- Although numerous current technology development activities are underway, available funding is insufficient to achieve TRL 6 in time for PDR in the mid-2020s

Questions?