Initial Technology Assessment for the Large UV-Optical-Infrared (LUVOIR) Mission Concept Study

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With help from the LUVOIR Science & Technology Definition Team, Study Office, and Technology Working Group

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A Brief History of LUVOIR

• pre-2010: Advanced Technology Large Aperture Space Telescope (ATLAST) mission concept study

• 2010: 2010 Decadal Survey, New Worlds, New Horizons
  – “...lay the technical and scientific foundations for a future space imaging and spectroscopy mission...” [page 20]
  – Recommended the definition of a future UV-optical space telescope

• 2013: NASA Astrophysics 30-year Roadmap
  – First mention of LUVOIR as a “Formative Era” mission

• 2013+: Additional work on ATLAST
  – Goddard, JPL, Marshall, Space Telescope Science Institute

• 2015: AURA From Cosmic Births to Living Earths
  – Recommend the High Definition Space Telescope

• 2016: Formation of LUVOIR Science & Technology Definition Team
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For a much more detailed history, see:

The LUVOIR STDT

• Tasked with:
  – Identify a compelling science case
  – Define a design reference mission with strawman payload
  – Prioritize and roadmap necessary technologies

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See poster 9904-181 for more details on the LUVOIR study plan
LUVOIR Science*

• Broad array of general astrophysics
  – Wide-field of view, high-resolution imaging in the Hubble bandpass (UV – NIR)
  – Wide-field of view, multi-object UV spectroscopy
  – Sensitivity at wavelengths at least as short as 100 nm

• Direct imaging of dozens of habitable exoplanets
  – Spectroscopic search for biosignatures
  – High-precision astrometry and/or radial velocity
  – Comparative planetology

• Local solar system observations

*Subject to further definition by the STDT
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Implies a need for precision UV optics and sensitive UV detectors.

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## Technology Prioritization for 2016 Cycle

<table>
<thead>
<tr>
<th>Technology Area</th>
<th>Difficulty</th>
<th>Urgency</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-Contrast Segmented-Aperture Coronagraphy</td>
<td>CRITICAL</td>
<td>CRITICAL</td>
</tr>
<tr>
<td>Ultra-Stable Opto-mechanical Systems (includes Sensing, Control, Mirrors, and Structures)</td>
<td>CRITICAL</td>
<td>CRITICAL</td>
</tr>
<tr>
<td>Large Format, High Sensitivity, High-Dynamic Range UV Detectors</td>
<td>HIGH</td>
<td>HIGH</td>
</tr>
<tr>
<td>Vis/NIR Exoplanet Detectors</td>
<td>HIGH</td>
<td>MED</td>
</tr>
<tr>
<td>Starshade</td>
<td>HIGH</td>
<td>MED</td>
</tr>
<tr>
<td>Mirror Coatings</td>
<td>MED</td>
<td>MED</td>
</tr>
<tr>
<td>MIR (3–5 μm) Detectors</td>
<td>LOW</td>
<td>LOW</td>
</tr>
</tbody>
</table>
High-Contrast, Segmented-Aperture Coronagraphy

- Coronagraphy + large aperture (> 8m) provides high-yield exoEarth detection & characterization

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Goal</th>
<th>State-of-the-Art (WFIRST)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture Type</td>
<td>Obscured, Segmented</td>
<td>Obscured, Monolith</td>
</tr>
<tr>
<td>Raw Contrast</td>
<td>$1 \times 10^{-10}$</td>
<td>$8.54 \times 10^{-9}$</td>
</tr>
<tr>
<td>Inner Working Angle</td>
<td>$2 \lambda/D @ 1 \mu m$</td>
<td>$3 \lambda/D @ 0.55 \mu m$</td>
</tr>
<tr>
<td>Bandpass (Instantaneous)</td>
<td>10 – 20%</td>
<td>10%</td>
</tr>
<tr>
<td>Bandpass (Total)</td>
<td>400 nm – 1.8 \mu m</td>
<td>523 nm – 578 nm</td>
</tr>
<tr>
<td>Throughput</td>
<td>&gt; 10 %</td>
<td>&lt; 5 %</td>
</tr>
<tr>
<td>LOWFSC Controllable Modes</td>
<td>Pointing, Z4-Z11</td>
<td>Pointing</td>
</tr>
<tr>
<td>LOWFSC Speed</td>
<td>&gt; 1 kHz</td>
<td>~1 kHz</td>
</tr>
<tr>
<td>LOWFSC Accuracy</td>
<td>&lt; 10 pm RMS</td>
<td>&lt; 0.5 mas RMS per axis</td>
</tr>
<tr>
<td>Post-processing Contrast Gain</td>
<td>&gt; 10×</td>
<td>3×</td>
</tr>
</tbody>
</table>
High-Contrast, Segmented-Aperture Coronagraphy

• Recommendations:

  – Continue the Segmented Coronagraph Design & Analysis study:
    • Improve model fidelity with dynamics, wavefront error, etc.
    • Continue “cross-pollination” and design collaboration

  – Viable candidates must be demonstrated on a UV-compatible, segmented aperture testbed prior to 2020 Decadal Survey
    • Need to establish credibility of segmented aperture coronagraphy
Ultra-Stable Opto-Mechanical Systems

• High-contrast imaging with a coronagraph requires wavefront stability ~10 pm RMS per wavefront control step

• Three general components to achieving wavefront stability:
  – Sensing Technologies
  – Control Technologies
  – Stable Structures & Mirrors

• An architecture involving all three is likely necessary to achieving the necessary stability
Sensing Technologies:

• **Image-based techniques**
  – Use the light from the object being observed
    • e.g. Zernike wavefront sensor, phase retrieval, etc.
  – Usually photon-starved, and therefore slower
    • Wavefront updates at 10s of minutes or hours

• **External metrology**
  – Use absolute metrology of optical system
    • e.g. laser trusses, edge sensors, etc.
  – Can be made arbitrarily fast, at the expense of added complexity
    • Provide wavefront updates at a few Hertz

• **Use both:**
  – Image-based techniques to control slow thermal drifts
  – External metrology to control faster dynamic drifts
Control Technologies:

• Primary Mirror Segments
  – Rigid body actuation in 6 degrees-of-freedom (a la JWST)
  – Higher-order control via warping harness or embedded actuators

• Macro-scale deformable mirrors
  – Currently used by most coronagraphs for speckle nulling
  – Continuous facesheets

• MEMs deformable mirrors
  – Continuous facesheet or segmented
  – Segmented can be mapped 1-to-1 to primary mirror segments for fast control of segment (tip/tilt)

• All require stable, precise, fast electronics
Stable Structures and Mirrors:

• Thermally stable mirror materials
  – ULE®, Zerodur® for low CTE at room temperature
  – SiC for high thermal conductivity, low CTE at colder temps

• Thermally stable structures
  – Composites with low CTE, CME
  – Better understanding of joints and lurches

• Requires better modeling and validation of linearity assumptions at picometer levels
Ultra-Stable Opto-Mechanical Systems

• Recommendations:

  – Systems-level approach to solving the problem
    • Mirrors, structures, sensors, actuators, materials, modeling, and the overall architecture must be developed together

    • Substantial participation of industry is necessary

  – Design and development activities to demonstrate closed-loop picometer-class stability for segmented apertures

  – Competitive development of picometer component sensing and control technologies and architecture feasibility demonstrations
Large Format, High Sensitivity, High Dynamic Range UV Detectors

- Micro-channel Plates (MCPs) are current state-of-the-art for UV detectors
  - Limited dynamic range (cannot view bright objects)
  - Limited lifetime (“gain-sag” issue)
  - Difficult to tile in large arrays

- EMCCD & sCMOS are of interest
  - *Must first be evaluated for radiation hardness and noise performance*
  - Could provide a path for large-format, high dynamic range
  - Need improvement in UV sensitivity
### Large Format, High Sensitivity, High Dynamic Range UV Detectors

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<tr>
<th>Parameter</th>
<th>Goal</th>
<th>State-of-the-Art (MCP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operational Bandpass</td>
<td>90 nm – 400 nm</td>
<td>90 nm – 300 nm</td>
</tr>
<tr>
<td>Read Noise</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Dark Current</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Spurious Count Rate</td>
<td>≤ 0.05 counts / cm² /s</td>
<td>0.05 counts / cm² /s</td>
</tr>
<tr>
<td>Quantum Efficiency (Peak)</td>
<td>75 % (FUV – NUV)</td>
<td>45 – 20% (FUV – NUV)</td>
</tr>
<tr>
<td>Resol Size</td>
<td>≤ 10 μm</td>
<td>20 μm</td>
</tr>
<tr>
<td>Dynamic Range</td>
<td>≥ 10⁴ Hz / resol</td>
<td>40 Hz / resol; 5 MHz global</td>
</tr>
<tr>
<td>Time Resolution</td>
<td>≤ 100 ms</td>
<td>&lt;&lt; 1 ms</td>
</tr>
<tr>
<td>Format</td>
<td>≥ 8 – 16 k pixels per side</td>
<td>8k x 8k</td>
</tr>
<tr>
<td>Radiation Tolerance</td>
<td>Good</td>
<td>Good</td>
</tr>
</tbody>
</table>
Recommendations:

- Technology-only balloon/rocket programs and laboratory demonstration can accelerate development
  - Minimize time spent on science instrumentation; focus on detector evaluation

- Evaluate/develop EMCCD and sCMOS for radiation hardness and noise performance
  - If acceptable, pursue δ-doping for UV sensitivity
  - Also benefits the Vis/IR Detectors for Exoplanet Science technology need
Vis/IR Detectors for Exoplanet Science

• For high exoEarth yields, require extremely low-noise detectors
  – < 1 e⁻/pixel read noise; < 0.0010 counts/pixel/s dark current

• Candidate technologies:
  – EMCCD:
    • Must be made radiation hard
  
  – sCMOS:
    • Must be evaluated for read noise, dark current, and radiation hardness

  – MKID/TES:
    • Energy resolving detectors require cryogenic operation which may be incompatible with picometer stability requirement
Starshade

• Alternative means to starlight suppression for exoplanet science
  – Trades telescope stability for added complexity of additional spacecraft flying in precise formation with observatory
  – Risk reduction should coronagraphy or stability prove too challenging
  – Mission enhancing for NIR exoplanet characterization

• Starshade Readiness Working Group (SSWG) recently formed
  – Develop “a technical concept and risk reduction plan” for starshade validation
Mirror Coatings

• Require broadband, high-performance coatings that are compatible with coronagraphy:
  – Maintain high reflectivity over band between 90 nm and 2.5+ μm
  – High uniformity over 10-m class aperture
  – Minimize polarization aberration and cross-polarization leakage

• Need investigations in deposition processes to improve reflectivity and uniformity

• Demonstration of high-contrast imaging with UV-compatible coated segmented aperture is needed prior to 2020
MIR (3-5μm) Detectors

• Depending on operating temperature of LUVOIR, varying degrees of MIR science is possible
  – Observations are limited by telescope’s thermal background
  – Even with a room-temperature telescope, cold instruments can enable some MIR transit spectroscopy

• Need to better understand needs of science observations relative to background limitations
  – Define detector needs and evaluate the technology gap
Conclusion

• Prioritized 7 technologies for LUVOIR, based on preliminary science case

• Three technologies elevated as urgent for 2016 investment:
  – High Contrast, Segmented Aperture Coronagraphy
  – Ultra-stable Opto-mechanical Systems
  – Large Format, High Sensitivity, High Dynamic Range UV Detectors

• Additional technologies will require development as
  – (a) the science case is further defined,
  – (b) the above gaps begin to narrow, and/or
  – (c) additional information is made available about current capabilities