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# The Large UV/Optical/Infrared Surveyor (LUVOIR): Decadal Mission Concept Technology Development Overview

Matthew R. Bolcar<sup>\*a</sup>

<sup>a</sup>NASA Goddard Space Flight Center, 8800 Greenbelt Rd., Greenbelt, MD, 20771 USA;

## ABSTRACT

The Large Ultraviolet / Optical / Infrared (LUVOIR) Surveyor is one of four large mission concept studies being developed by NASA for consideration in the 2020 Astrophysics Decadal Survey. LUVOIR will support a broad range of science objectives, including the direct imaging and spectral characterization of habitable exoplanets around sun-like stars, the study of galaxy formation and evolution, the epoch of reionization, star and planet formation, and the remote sensing of Solar System bodies. The LUVOIR Science and Technology Definition Team (STDT) has tasked a Technology Working Group (TWG), with more than 60 members from NASA centers, academia, industry, and international partners, with identifying technologies that enable or enhance the LUVOIR science mission. The TWG has identified such technologies in the areas of Coronagraphy, Ultra-Stable Opto-mechanical Systems, Detectors, Coatings, Starshades, and Instrument Components, and has completed a detailed assessment of the state-of-the-art. We present here a summary of this technology assessment effort, as well as the current progress in defining a technology development plan to mature these technologies to the required technology readiness level (TRL).

**Keywords:** space telescopes, ultraviolet, optical, infrared, coronagraphy, ultra-stable systems

## 1. INTRODUCTION

In 2016, NASA's Science Mission Directorate Astrophysics Division commissioned the study of four large mission concepts in preparation for the 2020 Decadal Study<sup>1</sup>: the Large UV/Optical/Infrared Surveyor (LUVOIR), the Habitable Exoplanet Imager (HabEx), the Origins Space Telescope (OST, formerly the Far-Infrared Surveyor), and Lynx (formerly the X-ray Surveyor). Each study is guided by a Science and Technology Definition Team (STDT) charged with defining a compelling science case for the mission. Shortly after convening, the STDT organized into six working groups (WGs):

- *Cosmic Origins WG*: Defines the general astrophysics science case for LUVOIR
- *Exoplanets WG*: Defines the exoplanet science case for LUVOIR, including the search for biosignatures
- *Solar System WG*: Defines the solar system and planetary science case for LUVOIR
- *Simulations WG*: Develops software to simulate the performance of LUVOIR and its instruments, in support of defining mission capabilities
- *Communications WG*: Coordinates outreach activities to the scientific community and general public, and develops materials in support of that goal
- *Technology WG*: Identify and prioritize technologies that will enable or enhance the LUVOIR mission, assess the technology gap between today's state-of-the-art and what is needed, and develop a plan to mature the technologies for a possible LUVOIR mission

The Technology Working Group (TWG) quickly began recruiting subject matter experts from industry, academia, other NASA centers, and international partners, and now has more than 60 members. In June of 2016, the TWG completed an initial technology prioritization, identifying seven potential technology needs and prioritizing them based on the difficulty and urgency<sup>2</sup>. This initial prioritization was largely done in anticipation of what LUVOIR might become; at this point in time, the STDT had not yet begun defining the science case, let alone make decisions about key architecture aspects such as aperture size, instrument complement, etc. Instead, the TWG drew on LUVOIR precursor studies, namely the Advanced Technology Large Aperture Space Telescope (ATLAST)<sup>3</sup>, and the High Definition Space Telescope (HDST)<sup>4</sup>.

\*matthew.bolcar@nasa.gov; phone 1 301 286-5237; fax 1 301 286-0204; www.nasa.gov/goddard

Through the latter half of 2016 and early 2017, the LUVOIR STDT defined a compelling science case while the LUVOIR Study Office (at NASA’s Goddard Space Flight Center (GSFC)) began developing the first of two mission architectures. The TWG itself organized into 5 subgroups that largely matched the original list of prioritized technologies:

- *Coronagraphy*
- *Ultra-stable Opto-mechanical Systems*
- *Detectors*
- *Coatings*
- *Instrument Components*

When the LUVOIR STDT chose a coronagraph as one of the instruments to be studied in detail as part of the design effort, the Coronagraphy subgroup was combined with the coronagraph instrument team. This team had the responsibility of defining specific performance capabilities to inform the instrument design study, and was best suited to evaluate and trade the different candidate technologies for the instrument. The reader is referred to L. Pueyo, *et al.*<sup>5</sup> for more details on the LUVOIR Architecture “A” coronagraph instrument.

The remaining four subgroups began a detailed technology assessment of a broad array of technologies that would enable or enhance the mission concept being studied. In mid-2017, the TWG released an updated technology prioritization and summary of the assessment process to NASA HQ. In this paper we discuss this technology prioritization and assessment. For a more detailed description of the LUVOIR Architecture “A” design, the reader is referred to a companion paper by Bolcar, *et al.*<sup>6</sup> in this volume.

The rest of the paper is organized as follows: Section 2 presents the newest LUVOIR Technology Prioritization, Sections 3 through 7 discuss each of the technology areas in detail, and Section 8 concludes and discusses future work.

## 2. LUVOIR TECHNOLOGY PRIORITIZATION

Figure 1 shows the most current technology prioritization for the LUVOIR Mission Concept Study. The technologies are grouped into five high-level categories. The technology readiness level<sup>7</sup> (TRL) for each technology is also reported. For each high-level technology, the TRL is a reflection of the maturity of the sub-technologies when considered as part of a system.

For example, in the case of Ultra-stable Opto-mechanical Systems, each of the sub-technologies is at a higher TRL than the parent technology. This reflects the fact that there is an additional challenge in integrating the sub-technologies into a system that further reduces the TRL.

| Priority | Technology Gap Name   | TRL      |
|----------|---|----------|
| 1        | <b>Ultra-stable Opto-mechanical Systems</b>                   | <b>2</b> |
| 1a       | Segment Phase & Control                                       | 3        |
| 1b       | Dynamic Isolation Systems                                     | 4        |
| 1c       | Mirror Segments   | 5        |
| 2        | <b>High-contrast Segmented Aperture Coronagraphy</b>          | <b>3</b> |
| 2a       | Segmented-aperture Coronagraph Architecture                   | 3        |
| 2b       | Deformable Mirrors  | 4        |
| 2c       | Wavefront Sensing & Control                                   | 4        |
| 2d       | High-contrast Imaging Post-processing                         | 4        |
| 3        | <b>High Performance UV/Vis/NIR Detectors</b>                  |          |
| 3a       | Large-format High-dynamic Range UV Detectors                  | 4        |
| 3b       | Ultra-low Noise Detectors for Visible Exoplanet Science       | 5        |
| 3c       | Ultra-low Noise Detectors for NIR Exoplanet Science           | 5        |
| 4        | <b>Next Generation Microshutter Arrays</b>                    | <b>4</b> |
| 5        | <b>High Reflectivity Broadband FUV-to-NIR Mirror Coatings</b> | <b>3</b> |

**Figure 1** – LUVOIR technology prioritization and TRL assessment. All of the listed technologies are deemed enabling for the LUVOIR mission.

No TRL is reported for the high-level High Performance UV/Vis/NIR Detectors technology since each of the sub-technologies stand alone as individual elements, and do not get integrated into a larger system.

Even though High Reflectivity Broadband FUV-to-NIR Mirror Coatings is TRL 3, it is ranked last in priority because it has a very clear, low risk path to development that can be rapidly executed should appropriate funding be made available.

### 3. ULTRA-STABLE OPTO-MECHANICAL SYSTEMS

High-contrast ( $10^{-10}$ ) imaging and spectroscopy for exoplanet science is critically dependent on telescope optics and wavefront stability<sup>8,9,10</sup>. A challenging requirement on the opto-mechanical system is that of wavefront error stability on the order of 10 pm RMS per wavefront control step (~10s of minutes), within the specific spatial frequencies that correspond to the dark-hole region of the focal plane. For the LUVOIR segmented aperture architecture(s), several key technologies are required to enable sufficient thermal and dynamic stability, and are discussed in further detail in Sections 3.1 – 3.3.

#### *Current State-of-the-Art:*

**Laser Interferometer Space Antenna (LISA) Pathfinder:** The LISA pathfinder mission<sup>11</sup> is an existence proof of a spaceflight opto-mechanical system capable of achieving picometer-level stability (TRL 9). However, the demonstrated stability was not over the spatial or temporal frequencies required by LUVOIR.

**James Webb Space Telescope:** When launched, JWST will exhibit the state-of-the-art for large aperture space telescopes in just about every area of performance, including wavefront stability. The expected wavefront stability is ~50 nm RMS per 14 day control period (TRL >6).

**Wide-field Infrared Survey Telescope (WFIRST):** The WFIRST Coronagraph Instrument (CGI) will be the first on-orbit demonstration of a high-contrast imaging system operating at a contrast of  $\sim 10^{-8}$ . While the level of wavefront stability to achieve this contrast is not sufficient for LUVOIR, WFIRST CGI will be a critical precursor technology demonstration for all future missions with a high-contrast coronagraph, providing invaluable experience in the design, integration, test, and operation of a large space telescope with single-digit nanometer, or sub-nanometer wavefront stability (TRL 6).

#### *Assessed Technology Readiness Level for LUVOIR:*

While the above state-of-the-art represents a TRL range from 6-9, when applied to the LUVOIR performance needs, the TRL necessarily drops. TRL 3 requires a demonstration of “analytical and experimental critical function and/or characteristic proof of concept. While numerous analytical activities are under way, an end-to-end proof-of-concept model of the LUVOIR system has not yet been completed, resulting in an assessed TRL of 2.

#### *Technology Advancement Objectives:*

**TRL 3:** Perform model-based systems-level studies that predict component technologies working together in an architecture to deliver the required stability. Such models may include integrated structural, thermal, optical models of the system with relevant thermal and dynamic inputs. End-to-end telescope-coronagraph optical models may also be used to verify stability requirements at specific spatial frequencies, the potential relaxation of stability requirements, and closed-loop control system architectures using different wavefront sensing and metrology inputs.

**TRL 4:** Perform hardware demonstrations of key technology components that indicate those components working at the required performance predicted by the above models.

**TRL 5:** Repeat the TRL 4 component hardware demonstrations, but in the presence of realistic thermal and dynamic disturbances that LUVOIR would experience on orbit, and show that the fundamental performance is not limited by the environment, but by the hardware components themselves.

**TRL 6:** A TRL 6 demonstration requires a system or subsystem model or prototype demonstration. Thus the component technologies need to be integrated into a scale testbed traceable to the LUVOIR architecture and achieve a level of performance that is both required by LUVOIR and predicted by validated models.

#### **3.1 Segment Phasing and Control**

Both of the LUVOIR architectures are expected to use deployable segmented primary mirrors to enable a large collecting aperture. Diffraction-limited phasing of such segmented systems using image-based phase retrieval will be demonstrated by JWST in 2018. However, maintaining picometer-level phasing between segments during long-duration coronagraph observations will require new sensing and control architectures, including: edge sensors (capacitive, inductive, or optical),

laser metrology, artificial guide stars, and picometer-level actuators for both rigid body and surface figure correction. For more details on the LUVOIR ultra-stable architecture, the reader is referred to Feinberg, *et al.*<sup>12</sup>

*Current State-of-the-Art:*

**LISA Pathfinder:** The laser metrology system<sup>11</sup> exceeded the performance requirement achieving picometer-level measurements at mHz bandwidths (TRL 9).

**Hubble Space Telescope (HST):** Piezoelectric (PZT) actuators with necessary stroke and precision have flight heritage on Wide Field Camera 3, though custom control electronics are likely necessary for LUVOIR applications (TRL 9).

**JWST:** Will achieve ~6 nm RMS rigid body positioning error and ~50 nm RMS stability over a 14-day period using image-based phase retrieval (> TRL 6).

**Space Interferometry Mission (SIM):** Technology demonstration for this mission led to picometer-level laser metrology<sup>13</sup>, but not in a configuration traceable to the LUVOIR architecture (TRL 5).

Capacitive gap sensors operating at hundreds of Hz with ~10pm sensitivity, feeding back to PZT control of an etalon cavity has been demonstrated in a laboratory setting (TRL 4).

Lab demonstrations of laser metrology systems with nanometer-level performance in a configuration similar to what might be needed by LUVOIR, consistent with high-contrast imaging applications have been completed. (TRL 4).

Ground-based telescope edge sensor systems<sup>14</sup> demonstrate the basic control system architecture implemented on LUVOIR, however additional work is needed to develop edge sensor geometries for efficiently measuring six degrees of freedom of segment position (TRL 4).

*Assessed Technology Readiness Level for LUVOIR:*

Even when evaluated against the performance needs of LUVOIR, all of the above demonstrations constitute a characteristic proof-of-concept of the technology, resulting in a TRL of 3.

*Technology Advancement Objectives:*

**TRL 4:** Demonstrate a closed-loop sense and control architecture between (at least) two subscale segments, operating at appropriate bandwidths and resolutions. The performance requirements of the sensors and actuators should be tied to predictions from the over-arching system-level TRL 3 demonstration.

**TRL 5:** Demonstrate the same closed-loop sense and control architecture in the presence of dynamic and thermal disturbances that are traceable to what LUVOIR would experience on orbit.

**TRL 6:** Repeat the TRL 5 demonstration on a sub-scale or full-scale segmented system that is traceable to the LUVOIR architecture.

### 3.2 Dynamic Isolation Systems

Passive and active isolation and damping of dynamic disturbances will be required to maintain the required picometer-level wavefront error stability. It is likely a tiered approach will be required, with passive isolation at the disturbance sources (i.e. the attitude control system actuators on the spacecraft) and active isolation of the payload from the spacecraft.

*Current State-of-the-Art*

**JWST:** Will demonstrate 80 dB of passive attenuation at frequencies > 40 Hz (>TRL 6).

Lockheed Martin's disturbance-free payload (DFP) demonstrated broadband isolation at better than 60 dB (all frequencies), and better than 80 dB at many frequencies between 1 and 20 Hz (TRL 4)<sup>15</sup>. These measurements have been used in integrated modeling studies of ATLAST, a precursor study to LUVOIR, and indicate these levels of isolation are acceptable, when coupled with TRL 9 passive isolators at the disturbance sources (reaction wheels).

*Assessed Technology Readiness Level for LUVOIR:*

The Lockheed Martin DFP demonstration consists of a component and/or breadboard validation in a laboratory environment. When combined with the integrated modeling done for ATLAST that indicates such a system can result in picometer-level wavefront stability, this technology is assessed to be TRL 4.

*Technology Advancement Objectives:*

**TRL 5:** Repeat the TRL 4 demonstration with flight-traceable control electronics and in the presence of dynamic disturbances that are traceable to what the LUVOIR payload would receive from the spacecraft.

**TRL 6:** Integrating the isolation system to a segmented optical system and showing stability of the co-phasing of the segments in the presence of a flight-like disturbance source would constitute a system model demonstration.

### 3.3 Mirror Segments

Both of the LUVOIR architectures will require mirror segments that achieve diffraction-limited performance at 500 nm, have high stiffness (>200 Hz) for dynamic stability, and thermal stability consistent with the overarching picometer-level wavefront stability requirement.

*Current State-of-the-Art:*

**JWST:** Beryllium mirror segments, 1.32-m flat-to-flat with 25 nm surface figure error (TRL 6).

The Multiple Mirror System Demonstrator (MMSD)<sup>16</sup> demonstrated fabrication or partial fabrication of five, 1.4-meter point-to-point ULE mirror segment substrates, achieving 10 kg/m<sup>2</sup> areal density and a production schedule of 3 mirrors on three-week centers. One of the five mirror segment substrates was flight qualified. Thermal modeling performed with as-measured CTE distributions indicate that these fabricated mirrors can achieve the necessary thermal stability for LUVOIR when properly controlled<sup>REF</sup> (TRL 5).

The Active Hybrid Mirror (AHM) program developed multiple fully-integrated and actuated 1.35-m SiC substrate mirror segment systems for visible applications, one of which has been flight qualified at TRL 6. Adding the necessary polished Si cladding layer to achieve the required wavefront error lowers this TRL to 4.

*Assessed Technology Readiness Level for LUVOIR:*

The LUVOIR Architecture “A” baselines the use of glass ULE mirror segments, thus the TRL is 5.

*Technology Advancement Objectives*

**TRL 6:** Demonstrate a fully integrated mirror segment system (including mounts, thermal control, actuators, and support structure) that meets mirror figure requirements, including segment-to-segment figure matching and flight qualify through vibrate, shock, and acoustic testing.

To fully explore mirror architecture trades, a competitive, industry-driven mirror development program should be pursued, wherein 2 or 3 mirror architectures are developed, eventually downselecting to a flight candidate architecture.

## 4. HIGH-CONTRAST SEGMENTED-APERTURE CORONAGRAPHY

One of the primary science goals of LUVOIR is to detect and characterize habitable exoplanets around nearby stars. To achieve exoplanet yields large enough to enable a statistical study of habitability requires a large aperture telescope, greater than 8 meters in diameter. Such an aperture must be segmented in order to fit into current and planned launch vehicle fairings. Therefore, any coronagraphic instrument that is used to perform the exoplanet survey and characterization must be compatible with a segmented aperture telescope. Several key technology components are required to enable these observations, including: coronagraph architecture, deformable mirrors, wavefront sensing, and post-processing techniques, and are discussed in detail in Sections 4.1 – 4.4.

*Current State-of-the-Art:*

**WFIRST:** Recent achievements<sup>17</sup> have demonstrated  $\sim 10^{-8}$  contrast at an inner working angle (IWA) of  $3 \lambda/D$  over a 10% bandpass with a significantly obscured monolithic aperture, but at limited throughput of the planet PSF (TRL 6).

The segmented coronagraph design and analysis (SCDA)<sup>18</sup> study, run by the Exoplanet Exploration program office, has yielded several coronagraph designs that theoretically achieve high contrast ( $10^{-10}$ ) over 15% bandpasses at IWAs of 3-4  $\lambda/D$  with throughputs as high as 30% - all with segmented apertures traceable to the LUVOIR architectures. Additional modeling is necessary to understand the impact of dynamic wavefront error disturbances, stellar diameter, and other noise sources (TRL 3).

*Assessed Technology Readiness Level for LUVOIR:*

The SCDA simulations constitute a characteristic proof-of-concept, thus this technology is TRL 3.

*Technology Advancement Options:*

**TRL 4:** Continue the SCDA study to model coronagraph performance with realistic noise inputs, including dynamic disturbances and stellar diameter. Perform testbed demonstrations of the coronagraph designs and achieve moderate contrasts ( $10^{-8}$  or better) over 15% bandpass at relevant inner working angles. Correlate the testbed demonstration with the models that predict  $10^{-10}$  contrasts.

**TRL 5:** Perform testbed demonstrations of coronagraph designs that achieve flight requirements on contrast, bandpass, IWA, and throughput, in the presence of expected dynamic and thermal instabilities.

**TRL 6:** Develop a prototype coronagraph instrument that incorporates flight-like masks, deformable mirrors, and optics, including a segmented aperture front-end telescope system. Achieve flight requirements on contrast, bandpass, IWA, and throughput in the presence of expected dynamic and thermal instabilities.

#### **4.1 Segmented-Aperture Coronagraph Architecture**

The design of coronagraph masks (apodizers, occulters, Lyot stops) and architectures fundamentally determines what contrast will ultimately be achievable by the coronagraph, and over what spatial frequencies and bandpasses. The coronagraph design also has a large impact on the overall throughput and sensitivity of the coronagraph to wavefront error instability. Additional coronagraph backend architectures (integral field spectrometers, fiber fed spectrometers, etc.) can enable observational efficiencies by allowing multiplexed object characterization.

*Current State-of-the-Art:*

**Hybrid Lyot (HL) / Shaped-Pupil Coronagraph (SPC):** WFIRST CGI has demonstrated  $10^{-8}$  contrast as part of the WFIRST CGI technology development program, with a significantly obscured aperture (TRL 6).

**Apodized Pupil Lyot Coronagraph (APLC):** The SCDA study resulted in several designs that achieve the necessary contrast, IWA, bandpass, and throughput to enable the LUVOIR science, but require additional modeling to understand the impact of wavefront instability and stellar diameter (TRL 3)

**Vector Vortex Coronagraph (VVC):** The SCDA study resulted in several designs that achieve the necessary contrast, IWA, and bandpass to enable the LUVOIR science, but throughput was significantly impacted by the on-axis obscuration. Additional optimization is needed to improve design throughput, as well as understand the impact of wavefront instability and stellar diameter (TRL 3).

**Visible Nulling Coronagraph (VNC):** A lateral shearing VNC has been demonstrated at  $10^{-9}$  contrast at the necessary IWA, but narrowband and with no shear implemented. This demonstration was performed with a segmented DM at a pupil, thus constitutes a demonstration with a segmented aperture (TRL 3).

*Assessed Technology Readiness Level for LUVOIR:*

All of the above examples constitute a characteristic proof-of-concept when evaluated in the context of LUVOIR's performance needs, and thus achieves TRL 3.

*Technology Advancement Objectives:*

**TRL 4:** Continue the SCDA study to model coronagraph performance with realistic noise inputs, including dynamic disturbances and stellar diameter. Perform testbed demonstrations of the coronagraph designs and achieve moderate contrasts ( $10^{-8}$  or better) over 15% bandpass at relevant inner working angles. Correlate the testbed demonstration with the models that predict  $10^{-10}$  contrasts.

**TRL 5:** Perform testbed demonstrations of coronagraph designs that achieve flight requirements on contrast, bandpass, IWA, and throughput, using flight-traceable components for masks and DMs, and expected dynamic and thermal instabilities.

**TRL 6:** Integrate the coronagraph testbed to a segmented aperture system and demonstrate closed-loop control of the system with expected dynamic and thermal instabilities.

## 4.2 Deformable Mirrors

Deformable mirrors (DMs) are key components of coronagraph instruments, responsible for correcting residual wavefront error to sufficiently suppress speckles in the coronagraph focal plane. Once contrast is achieved, the DMs must maintain contrast by correcting slow drifts in the rest of the optical system. When not actively being controlled, the DMs must remain stable so as to not introduce wavefront drift themselves. The outer working angle (OWA) of the coronagraph is fundamentally limited by the number of actuators across the diameter of the DM. Thus large format DMs are needed to enable greater fields-of-view.

### *Current State-of-the-Art:*

**WFIRST CGI:** Electrostrictive pmn-based Xinetics DMs have been used to demonstrate  $10^{-8}$  contrast<sup>17</sup> and are being baselined for the WFIRST CGI instrument (TRL 5).

Segmented MEMS DMs have been used in a laboratory setting to achieve  $5 \times 10^{-9}$  contrast in the visible nulling coronagraph (TRL 4).

Continuous facesheet MEMS DMs are routinely used on ground-based observatory systems to achieve moderate contrasts ( $10^{-5} - 10^{-6}$ ) (TRL 4).

### *Assessed Technology Readiness Level for LUVOIR:*

The existing devices constitute a component validation in laboratory environments, and thus are at TRL 4.

### *Technology Advancement Objectives:*

**TRL 5:** Continue to mature DM technology by flight qualifying the devices and electronics. Improve actuator counts to  $64 \times 64$  or larger. Demonstrate feed-forward control precision and repeatability consistent with LUVOIR wavefront sensing and control requirements.

**TRL 6:** Use either a MEMS or Xinetics DM in a  $10^{-10}$  contrast demonstration with a segmented aperture.

## 4.3 Wavefront Sensing (Low-Order and Out-of-Band)

The wavefront stability requirement to enable high-contrast imaging systems is typically quoted as 10 pm RMS per wavefront control step (typically 10s of minutes) over the relevant dark-hole spatial frequencies. The wavefront control step time is determined by the wavefront sensing technique and the number of source photons used to perform the sensing. Low-order wavefront sensing (LOWFS) typically uses stellar photons rejected by the coronagraph instrument occulting mask (which limits its spatial frequency sensitivity) to estimate line-of-site pointing and low-order (focus, astigmatism, coma) wavefront terms. Out-of-band wavefront sensing (OBWFS) uses stellar photons that are out of the observing wavelength or spatial frequency bands, allowing higher spatial frequency sensitivity.

### *Current State-of-the-Art:*

**WFIRST:** Low-order wavefront sensing has been demonstrated on a  $10^{-8}$  contrast coronagraph testbed with realistic disturbances input to the coronagraph optics. The LOWFS system demonstrated  $< 0.5$  mas RMS per axis line-of-site residual error and was sensitive to  $\sim 100$  pm of focus error (TRL 6).

Out-of-band wavefront sensing has been simulated with a LUVOIR like aperture and preliminary results show picometer-level sensitivity can be achieved for low and high-order terms with sufficient integration time (TRL 3).



*Assessed Technology Readiness Level for LUVOIR:*

The WFIRST LOWFS system represents a breadboard validation in a laboratory environment for LUVOIR and is therefore TRL 4.

*Technology Advancement Objectives:*

**TRL 5:** Demonstrate LOWFS and OBWFS systems on testbed with expected LUVOIR disturbances as input, correcting line-of-site pointing, defocus, and higher-order terms as needed to maintain the contrast level.

**TRL 6:** Combine the LOWFS and OBWFS system with a  $10^{-10}$  contrast coronagraph and demonstrate closed-loop control while maintaining contrast.

Additional development of off-axis techniques using OBWFS would also be of value, allowing the use of OBWFS with brighter, off-axis guide stars – either natural or artificial.

#### **4.4 High-contrast Imaging Post-processing**

Calibration and post-processing techniques allow the additional subtraction of stellar flux from an image, after data collection. This is a process necessary to achieve the highest contrast, thus defining the exoplanet detection floor. Achieving additional contrast factors of 10x-100x would enable significant improvements in the science yield of LUVOIR.

*Current State-of-the-Art:*

**HST:** Post-processing techniques have been used routinely on archival NICMOS coronagraphic images to improve contrast from raw levels of  $10^{-5}$  by an average of 300x, with detection of point sources 50x below the mean speckle intensity (TRL 9).

For ground based systems, additional factors of ~10x in contrast have been achieved for moderate contrast coronagraph systems ( $10^{-5}$  –  $10^{-6}$ ) (TRL 4).

*Assessed Technology Readiness Level for LUVOIR:*

The ground-based post-processing techniques would be equivalent to breadboard validation in a laboratory environment for LUVOIR, and are thus TRL 4.

*Technology Advancement Objectives:*

**TRL 5:** Post-processing techniques and algorithms need to be tested on simulated and/or real data with raw contrasts on the order of  $10^{-8}$  –  $10^{-10}$ , that include realistic background and noise fluxes.

**TRL 6:** Demonstrate 10x – 100x improvements in real data raw contrasts of at least  $10^{-9}$ , collected with a segmented aperture and coronagraph testbed traceable to the LUVOIR flight system.

## **5. HIGH-PERFORMANCE UV, VISIBLE, AND NIR DETECTORS**

Advances in detector sensitivity, format, dynamic range, and radiation tolerance are needed across the UVOIR band to enable the ambitious science goals of LUVOIR. In the FUV, large-format, high dynamic range detectors will enable multi-object spectroscopic observations at wavelengths as short as 100 nm. In the Optical and Near-IR, single photon, large format detectors will enable key exoplanet observations, including multiplexed spectral observations of exoplanet systems. Quantum efficiency improvements across the entire band will further enhance the LUVOIR science mission. Sections 5.1 – 5.3 discuss each sub-technology in more detail.

*Current State-of-the-Art:*

**WFIRST:** Development of the H4RG-10 detector package for tiling of large arrays and improvements in noise performance can be directly leveraged by several of LUVOIR's planned instruments (TRL 6). The EMCCD detectors baselined for the WFIRST CGI also provide a detector solution for LUVOIR's coronagraph instrument, however improvements in radiation tolerance would further enhance performance (TRL 6).

Sub-orbital sounding rocket missions have developed many aspects of micro-channel plate (MCP) technologies for use in the FUV. Large format, improved sensitivity, and high count-rate electronics have been demonstrated independently (TRL 4).

Laboratory demonstrations of  $\delta$ -doped silicon-based CMOS and CCD detectors have improved quantum efficiencies for near-UV applications (TRL 4).

*Assessed Technology Readiness Level for LUVOIR:*

All of the above detector technologies are directly relevant to the LUVOIR architectures, and thus the TRL is 4 – 6, depending on the specific detector and its application in the instrument.

*Technology Advancement Objectives:*

**EMCCD:** Additional radiation testing and design work to further improve radiation tolerance would enhance the exoplanet science yield for LUVOIR. Larger format arrays would also enhance the efficiency of high-resolution Integral Field Spectrograph (IFS) instrument designs.

**H4RG:** Characterization of H4RG detectors should be pursued to understand the viability of these detectors for NIR exoplanet science. Efforts to minimize readnoise in the readout electronics would further improve science yield.

**CMOS:** Large format CMOS arrays with improved quantum efficiency and high well-depth would enhance general astrophysics observations in the visible band.

**MCP:** Incorporating all aspects of recent sounding rocket demonstrations into a single, large format, high count rate, high quantum efficiency detector array for a sounding rocket demonstration would achieve LUVOIR's FUV detector needs.

**Superconducting detectors:** MKID, TES, and other similar superconducting detectors remain of interest as a potentially enhancing solution for zero read noise exoplanet observations with built-in spectral resolution. Additional development of these detectors, as well as ultra-low (zero) vibration cryocooler technologies may enhance the LUVOIR science mission.

## 5.1 Large-format, High-Dynamic Range UV Detectors

A principal goal for all technologies is the development of a large-format detector with high pixel count to allow for wide-field imaging and multi-object spectroscopy (MOS) in the UV. All technologies need additional development to achieve these high fill-factor focal planes with a large pixel count, while maintaining other capability requirements. Curved detectors that have the potential to simplify relay optics and reduce the number of reflections for wide-field of view performance should also be considered.

*Current State-of-the-Art:*

**SISTINE, FORTIS, CHESS:** These suborbital sounding rocket missions have incrementally matured aspects of micro-channel plate (MCP) detector technologies, including array size, photocathode sensitivity, and read-out electronics count rates (TRL 9).

Delta-doped silicon-based detectors such as CCD, EMCCD, and CMOS arrays offer new options in terms of format and dynamic range, but are less mature, less solar blind, and less radiation tolerant than MCP detectors (TRL 4).

*Assessed Technology Readiness Level for LUVOIR:*

While the individual sounding rocket demonstrations each constitute a TRL 9 demonstration by definition, incorporating all aspects of the MCP development (array size, sensitivity, electronics) into a single detector and tested in a relevant environment remains to be completed, thus dropping the TRL to 4.

*Technology Advancement Objectives:*

**TRL 5:** Incorporate all aspects of the sounding rocket development program into a single MCP detector demonstration that achieves the LUVOIR format, sensitivity, and count-rate requirements. Thorough flight qualification would further improve the TRL to 6.

Delta-doped silicon based detectors should continue to be developed to improve sensitivity, radiation tolerance, and solar blindness.

## 5.2 Ultra-low Noise Detectors for Visible Exoplanet Science

Exoplanet yield studies indicate that detectors with zero readnoise (i.e. photon counting) and very low dark current and spurious count rates maximize the exoplanet yield, and in some cases enable exoplanet spectroscopy with an integral field unit.

### *Current State-of-the-Art:*

**WFIRST:** EMCCD's have been baselined for the CGI instrument and meet the noise requirements for  $10^{-8}$  contrast and the radiation tolerance for a 5-year mission (TRL 6).

HMCCD technology is inherently radiation tolerant, but requires further development to demonstrate similar photon counting capabilities as EMCCD (TRL 3).

Superconducting detectors such as MKID and TES are inherently noise free and provide native spectral resolution in the detector substrate. However, the need for a cryocooler to achieve operating temperature may introduce unacceptable disturbances to the system. Larger format arrays are also needed (TRL 3).

### *Assessed Technology Readiness Level for LUVOIR:*

The LUVOIR Architecture "A" coronagraph instrument baselined the use of the same EMCCD arrays that are currently being developed by WFIRST. Additional improvements to detector packaging to enhance radiation hardness are needed, dropping the TRL to 5.

### *Technology Advancement Objectives:*

**TRL 6:** Additional development of EMCCDs to further improve radiation tolerance would enable peak performance of the coronagraph instrument over a longer instrument lifetime.

Development of the HMCCD detector technology would also solve the radiation tolerance problem while providing the same photon counting performance of EMCCDs.

Superconducting technologies should continue to be explored as a potential enhancing / backup option for LUVOIR.

## 5.3 Ultra-low Noise Detectors for Near-IR Exoplanet Science

As with the visible detectors, exoplanet yield studies indicate that detectors with very low readnoise and dark current are needed to maximize the yield.

### *Current State-of-the-Art:*

**WFIRST:** H4RG detectors developed for WFIRST already exhibit exceptionally good noise performance (single-digit read noise,  $10^{-3}$  dark current), as well as large-format tileable arrays (TRL 6).

Superconducting detectors such as MKID and TES are inherently noise free and provide native spectral resolution in the detector substrate. However, the need for a cryocooler to achieve operating temperature may introduce unacceptable disturbances to the system. Larger format arrays are also needed (TRL 3).

### *Assessed Technology Readiness Level for LUVOIR:*

The LUVOIR Architecture "A" coronagraph instrument baselined the use of the same H4RG detectors currently being developed for the WFIRST wide-field instrument. Small optimizations to the read-out electronics to further improve the readnoise to 1-2 e<sup>-</sup> is still needed, dropping the TRL to 5.

### *Technology Advancement Objectives:*

**TRL 6:** Characterization of H4RG detectors and optimization of the readout electronics for the goal of NIR exoplanet science should be carried out to confirm the ability to perform the necessary exoplanet science observations with these detectors.

Superconducting technologies should continue to be explored as a potential enhancing / backup option for LUVOIR

## 6. NEXT-GENERATION MICROSHUTTER ARRAYS

The LUVOIR UV Multi-object Spectrograph (LUMOS) instrument requires a 2 x 3 tiled-array of next generation microshutters to enable the multi-object mode of observation. These microshutters leverage the heritage from JWST's Near Infrared Spectrograph (NIRSpec) instrument, but add improvements to array size and shutter reliability.

### *Current State-of-the-Art:*

**JWST:** NIRSpec uses a 2 x 2 tile of microshutter arrays (MSAs), with each tile having a format of 171 x 365 shutters. A permanent magnet is swept across the array to actuate the shutters (> TRL 6).

Next-generation MSAs that eliminate the moving magnet and instead rely on low-voltage electrostrictive actuation have been demonstrated in the lab, with plans to fly on a sounding rocket in the near future (TRL 4).

### *Assessed Technology Readiness Level for LUVOIR:*

The demonstrated next-gen MSAs are directly applicable to LUVOIR, although they require engineering development to improve the format to 420 x 840 shutters and allow for array tiling. Thus the TRL remains at 4.

### *Technology Advancement Objectives:*

**TRL 5:** Environmental testing of the next-gen MSAs, including vibrate, shock, acoustic, and thermal-vacuum testing, would constitute a component validation in a relevant environment.

**TRL 6:** A tiled array of MSAs, each consisting of 420 x 840 shutters, needs to be demonstrated and subjected to the full range of flight qualifying environmental tests.

## 7. HIGH-REFLECTIVITY BROADBAND FUV-TO-NIR MIRROR COATINGS

General astrophysics and exoplanet science require high-throughput observations between 100 nm and 2.5  $\mu\text{m}$ . The coating should achieve >50% reflectivity at 105 nm while not compromising performance at wavelengths > 200 nm compared to existing state-of-the-art. The coating process must be scalable to meter-class segments and repeatable to ensure uniform performance across an aperture comprised of >100 segments.

### *Current State-of-the-Art:*

State-of-the-art Al+LiF coatings demonstrated on coupons exhibit the desired performance but suffer from environmental degradation due to hygroscopicity. Investments in improving deposition processes is needed, to provide repeatable, large scale results. The ability to deposit an additional thin capping layer of  $\text{MgF}_2$  or  $\text{AlF}_3$  would provide environmental stability while not affecting performance. Coating characterization is needed to perform polarization performance modeling and its impact on high-contrast imaging.

As to mirror cleaning, existing approaches (e.g.,  $\text{CO}_2$  snow, or electrostatic wands with AC excitation), do not remove molecular contamination. Promising methods (e.g., electron or ion beams) could clean off molecular layers as well as dust on substrates.

### *Assessed Technology Readiness Level for LUVOIR:*

Coupon demonstrations of Al+LiF+ $\text{AlF}_3$  have been performed, but are not yet optimized for maximum performance, or fully characterized for environmental stability. Still the deposition demonstrates a characteristic proof-of-concept and is therefore TRL 3.

### *Technology Advancement Objectives:*

**TRL 4:** Demonstrate the deposition of a protected Al+LiF+ $\text{MgF}_2$  or Al+LiF+ $\text{AlF}_3$  FUV-optimized coating on glass substrates and separate coating runs to verify repeatability of the process. Characterize coating reflectivity, uniformity, and polarization performance to verify the coatings achieve LUVOIR requirements.

**TRL 5:** Verify coating stability over time in ambient environments, as well as in a relevant radiation environment.

**TRL 6:** Demonstrate coating process on meter-class segments.

Techniques for last-minute ground or in-flight cleaning technology to remove molecular coatings as well as dust should also be pursued.

## 8. FUTURE WORK

As the LUVOIR Study continues to develop both architecture designs, it is likely that additional technology needs will be identified, or perhaps even some of the technology gaps assessed here may be retired. The TWG will continue to refine these technology gaps to respond to the evolving architectures, and update the technology prioritization and gap assessment in the summer of 2018.

In the meantime, the TWG is beginning the next phase of its effort to further define the tasks described in each Technology Advancement Objectives section. This involves surveying current technology development investments in each area, defining specific, actionable tasks that can be completed to achieve the very broad recommendations presented here, and estimating the cost and schedule required to execute those tasks.

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