# Astro2020 APC White Paper

# The Large UV / Optical / Infrared Surveyor (LUVOIR): Telling the Story of Life in the Universe


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## Key Science Goals & Objectives

Humanity is defined by the drive to know about the world around us. The value of that quest for the betterment of our species is immeasurable. Ages-old questions and investigations earned us the revelations that the stars are Suns swirling in a vast galaxy, itself one of a myriad of islands in an expanding cosmos. Now we have crossed another threshold of discovery: there are planets around other stars (e.g., Mayor & Queloz 1995). At this key point in human history, tracing a path from the dawn of the universe to life-bearing worlds is within our grasp.

This monumental objective demands powerful and flexible new tools, as well as application of multi-disciplinary scientific skills. The abundance and diversity of worlds is far greater than imagined, yet there are planetary systems reminiscent of the solar system as well (e.g., Winn & Fabrycky 2015). At the moment, the vast majority of known exoplanets are "small black shadows" indirectly detected through their effect on their host stars. Our knowledge of exoplanet properties is largely limited to orbits, masses,

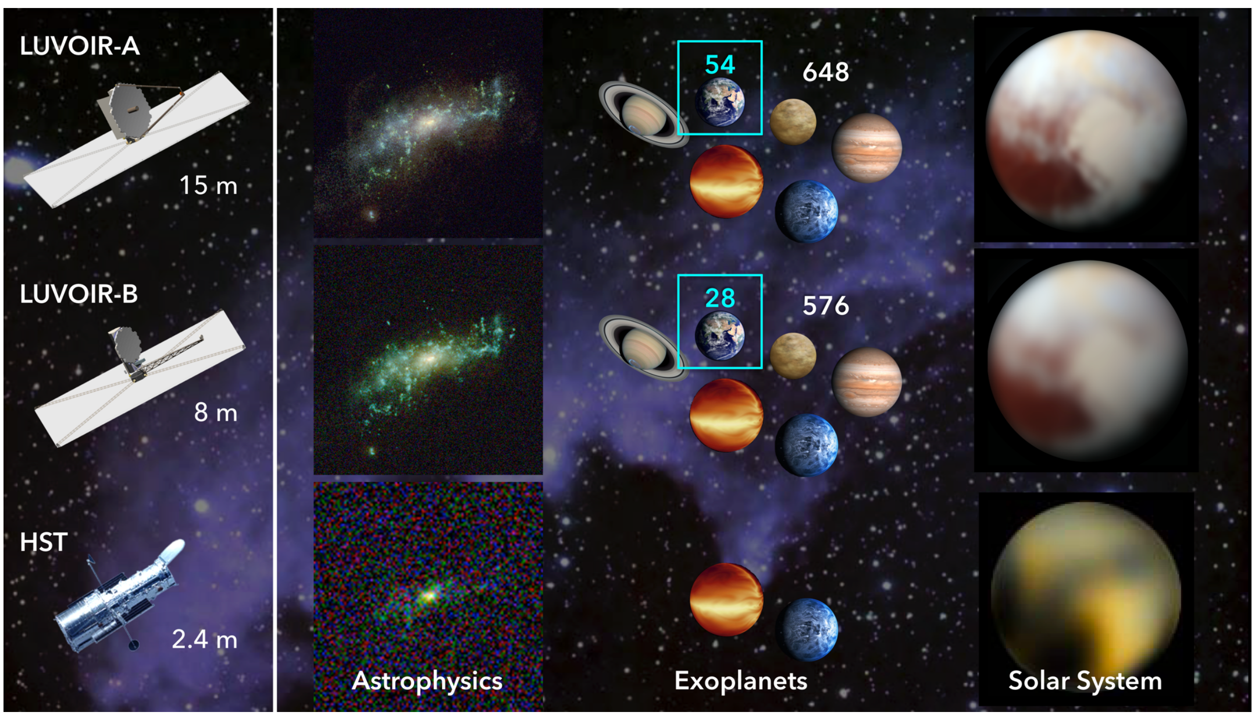


***Figure 1:*** *LUVOIR will revolutionize huge areas of space science. Its sensitivity and spatial resolution open the door to the ultra-faint and ultra-distant regime, enabling detailed observations of the full variety of galaxies. LUVOIR dramatically increases the sample size and diversity of exoplanets that can be studied, providing dozens of Earth-like exoplanet candidates that can be probed for signs of life (54 with LUVOIR-A and 28 with LUVOIR-B) and hundreds of non-habitable exoplanets (648 with LUVOIR-A and 576 with LUVOIR-B). Finally, LUVOIR will provide near-flyby quality observations of solar system bodies (HST Pluto image from Buie et al. 2010). Credits: NASA / New Horizons / M. Postman (STScI) / A. Roberge (NASA GSFC)*

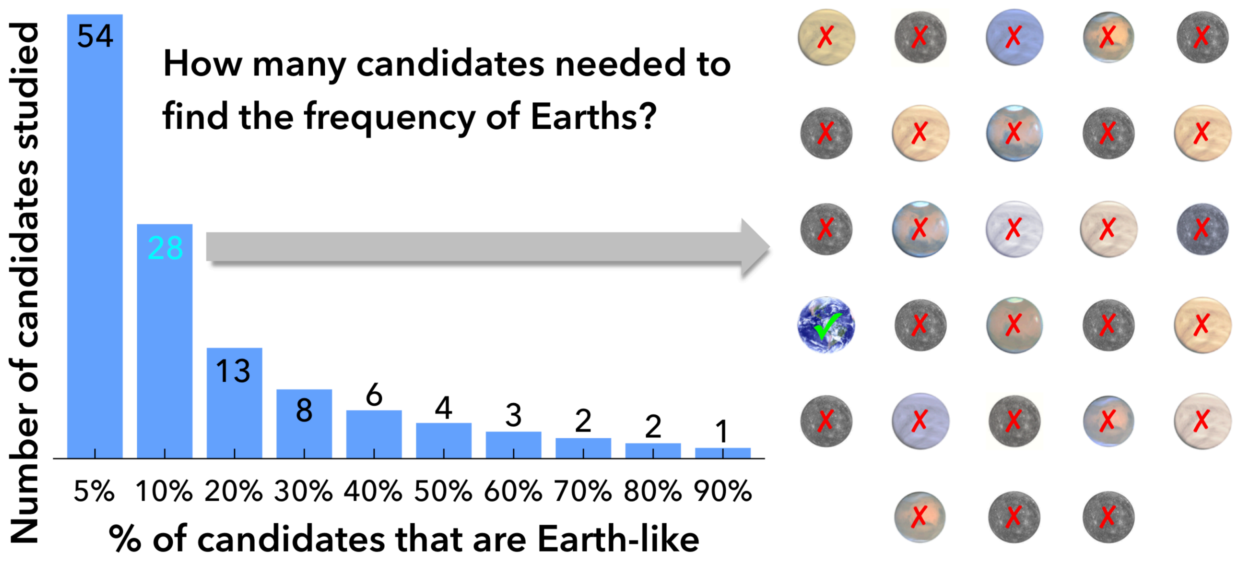


***Figure 2:*** *How many rocky habitable zone exoplanets need to be studied? The bar chart shows the number of candidates needed to discover one Earth-like planet (at the 95% confidence level), as a function of the percentage of temperate rocky planets that are actually Earth-like. If the percentage is 10%, then 28 candidates need to be observed. To put it another way, if 28 candidates are observed and no water vapor is detected, then we learn that* $< 10\%$ *of rocky planets in stellar habitable zones are actually Earth-like. Credit: C. Stark (STScI) / A. Roberge (NASA GSFC)*

and sizes. Astronomers have just begun to measure the atmospheric constituents of gas giant exoplanets; such studies will greatly expand in the coming years.

The next frontier is to extend these capabilities to rocky planets and find the "pale blue dots" in the solar neighborhood. With a large enough sample size, scientists can determine whether habitable, Earth-like conditions are rare or common on nearby worlds (**Figure 2**) and then probe them for signs of life (e.g., atmospheric oxygen). Focusing on the planetary systems most like the solar system, those with Earth-size exoplanets orbiting in the habitable zones of Sun-like stars, increases the chances of finding and recognizing atmospheric biosignatures (e.g., G. Arney, Astro2020 Science WP). Concurrently, we will nurture a new discipline – comparative exoplanetology – by studying a huge range of exoplanets, thereby gaining invaluable information for placing our own system in the broader context of planetary systems (e.g., M. Marley, Astro2020 Science WP). A vital part of establishing that context is deeper understanding of the bodies within the solar system (e.g., R. Juanola-Parramon, Astro2020 Science WP).

Our drive to know goes beyond asking the question "what exists?" to "why does it exist?" and pushes us to understand the origins of all we see around us. The boundary of what we can see now stretches all the way to the dawn of the universe, but like our first steps in the study of new worlds, our vision lacks both completeness and context. We seek to understand the environments and processes that gave rise to a life-supporting cosmos: from the formation of the earliest structures (**Figure 3**), to the assembly and evolution of galaxies (e.g., J. Tumlinson, Astro2020 Science WP), to the detailed mechanisms of star and planet formation (e.g., K. France, Astro2020 Science WP). The boundaries of physics will be tested and stretched while exploring the birth and evolution of the cosmos.

These scientific questions and investigations demand an observatory beyond any in existence or in development. They require a large aperture to capture the very faintest objects across cosmic time. They require the ability to block the blinding light from hundreds of stars and observe dozens of small, faint planets orbiting them. They require access to a range of wavelengths broad enough to read the fingerprints of matter across all temperatures and densities. These needs define the required tool, which is the Large Ultraviolet / Optical / Infrared Surveyor (LUVOIR).

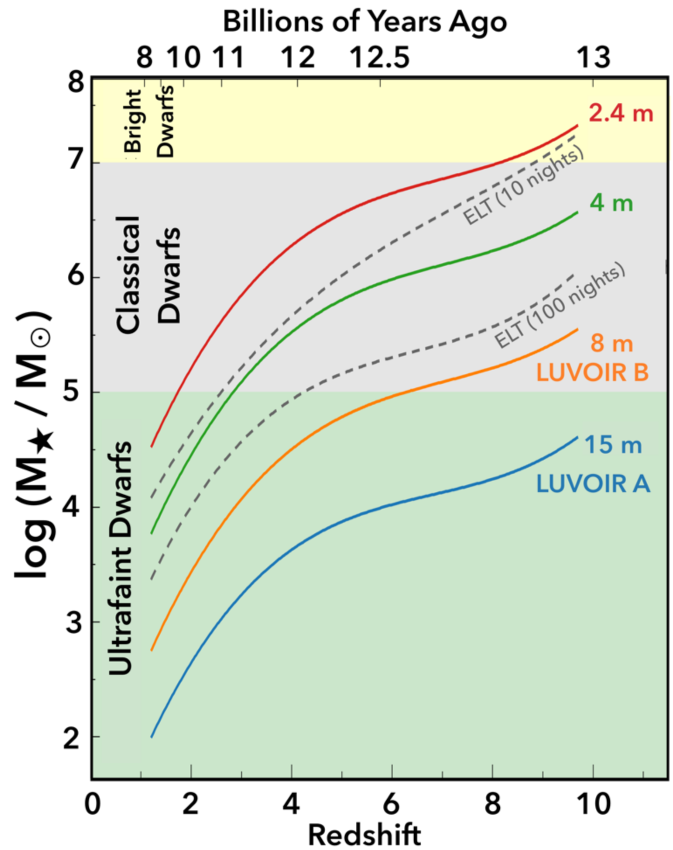


***Figure 3:*** *LUVOIR can detect the smallest galaxies at the earliest times. The plot shows the ability of various telescopes to detect dwarf galaxies of a particular total stellar mass (y-axis) as a function of redshift / lookback time: a 2.4-m space telescope, a 4-m space telescope, the LUVOIR concepts, and the 39-m ground-based ELT. Limits for space-based telescopes assume a 139 hour observation that returns a S/N=5 detection of a 200-parsec diameter source. Limits for the ELT are for a 10-night (80 hour) integration and a 100-night (800 hour) integration. The JWST limit is similar to the 100-night ELT limit. Credit: M. Postman (STScI)*

The LUVOIR mission concept is one of four Large Mission Concepts studied in preparation for the 2020 Astrophysics Decadal Survey (Astro2020). The study was initiated in Jan 2016, under the leadership of a Science and Technology Definition Team (STDT) drawn from the community[1]. Over the last 3.5 years, the STDT and the

[1] Team list at https://asd.gsfc.nasa.gov/luvoir/team/

LUVOIR engineering team – with valuable input and assistance from the broader community – have worked closely to produce one of the most detailed and mature large mission concepts ever presented to an Astrophysics Decadal Survey. The records and results of this work will be submitted to NASA HQ and Astro2020 in the form of a Final Report and additional technical material (e.g., master equipment lists).

***Table 1:*** *LUVOIR's Signature Science Cases*

| |
|---|
| # 1 – Finding habitable planet candidates |
| # 2 – Searching for biosignatures and confirming habitability |
| # 3 – The search for life in the solar system |
| # 4 – Comparative atmospheres |
| # 5 – The formation of planetary systems |
| # 6 – Small bodies in the solar system |
| # 7 – Connecting the smallest scales across cosmic time |
| # 8 – Constraining dark matter using high precision astrometry |
| # 9 – Tracing ionizing light over cosmic time |
| # 10 – The cycles of galactic matter |
| # 11 – The multiscale assembly of galaxies |
| # 12 – Stars as the engines of galactic feedback |

The LUVOIR Team has considered the best ways to present this large volume of information to Astro2020 in an effective, complete, and accessible fashion. We have therefore organized the Final Report in tiered layers of detail. The first level consists of an extended summary (Chapter 1) with an overview of the entire Final Report. Chapter 2 contains a roadmap to the report, intended to aid navigation through the document by identifying the locations of key material (e.g., science traceability matrices). In the next level, Chapters 3–6 present explanations of the science cases, while Chapters 7–13 explain the engineering design and the detailed technology development plan and schedule. The third level provides supporting details and calculations (Appendices A–K); these documents will be available in a separate PDF.

The scope of science enabled by LUVOIR is truly vast, encompassing all the topics addressed by Hubble and more. The LUVOIR STDT therefore decided to focus on a set of "Signature Science Cases" (**Table 1**). In Chapters 3–6 of the Final Report, we explain the motivations for the Signature Science Cases, identify key measurements, and set out needed observations. The telescope and instrument characteristics required for the observations are also identified. We have developed concrete observing programs for each Signature Science Case to ensure that the LUVOIR designs can execute this compelling science within the 5-year prime mission lifetime (Appendix B of the Final Report).

The Signature Science Cases represent some of the most compelling observing programs that scientists might do with LUVOIR at the limits of its performance. As compelling as they are, they should not be taken as a complete specification of LUVOIR's future scientific potential. Additional science cases contributed by the STDT and the broader community appear in Appendix A of the Final Report. Furthermore, the LUVOIR Team attempted to review all 593 Science White Papers (WPs) submitted to Astro2020; approximate numbers of WPs relevant to LUVOIR appear in **Table 2** (effort is currently incomplete for astrophysics WPs). We fully expect that the creativity of the community, empowered by the revolutionary capabilities of LUVOIR, will ask questions, acquire data, and solve problems beyond those discussed in the Final Report. Just as Hubble is today doing science not envisioned at the time of its design or launch, LUVOIR's power, flexibility, and potential longevity will allow it to execute the as-of-yet unknown science of the 2040s and beyond.

***Table 2:*** *LUVOIR in the Astro2020 Science White Papers*

| Description | # of papers |
|---|---|
| Explicit mentions of LUVOIR | 68 of 593 |
| Exoplanet WPs relevant to LUVOIR | 55 of 102 |
| Astrophysics WPs relevant to LUVOIR | >66 of 467 |
| Solar System WPs relevant to LUVOIR | 13 of 24 |

## Technical Overview

The LUVOIR Team developed two distinct observatory concepts: the 15-m LUVOIR-A (**Figure 4**), designed for launch in the SLS Block 2 vehicle; and the 8-m LUVOIR-B (**Figure 5**), designed to fit in heavy-lift launch vehicles with 5-m fairings similar to those in use today. By studying two designs, we gain better understanding of a complex trade space, reveal how science return scales with different technical choices, and establish robustness to uncertainties such as future launch vehicle capabilities and budget constraints. It is important to recognize that LUVOIR-A and -B represent proof-of-concept point designs within a family of UV/Optical/NIR observatories, demonstrating feasibility and providing information for the future. LUVOIR's main features are:

- Scalable, serviceable architecture for an observatory at Earth-Sun L2
- A 5-year prime mission, with 10 years of on-board consumables. Non-servicable components have a 25-year lifetime goal
- Large, segmented, deployable telescopes designed for launch in next-generation heavy lift vehicles with large fairings (e.g., NASA's SLS Block 2, NASA's SLS Block 1B Cargo, Blue Origin's New Glenn, and SpaceX's Starship)
- UV-capable telescopes that are compatible with high-contrast exoplanet observations (total wavelength range of 100–2500 nm)

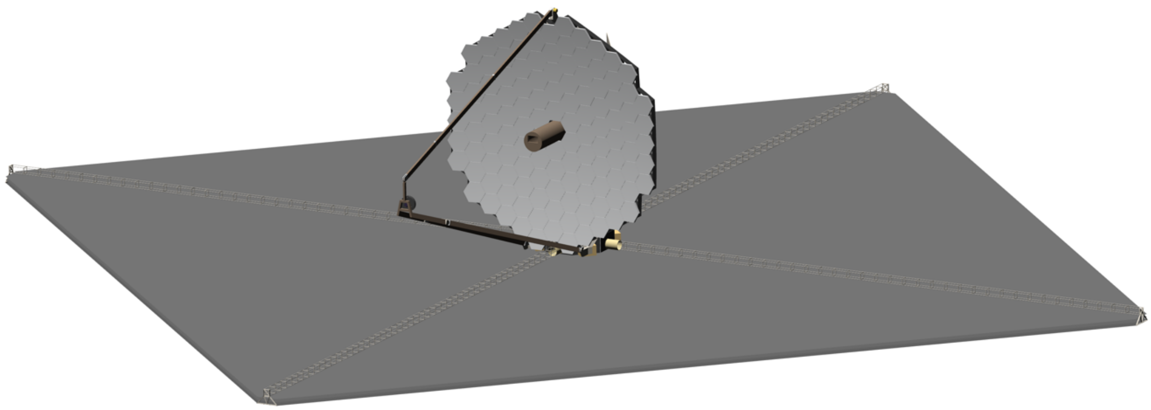

***Figure 4:*** *The LUVOIR-A observatory, with a 15-m diameter on-axis primary mirror and four instruments. Deployment and pointing animation at [https://asd.gsfc.nasa.gov/luvoir/design/](https://asd.gsfc.nasa.gov/luvoir/design/). Credit: A. Jones (NASA GSFC)*

- Telescope optical designs to alleviate polarization effects that can degrade coronagraph contrast (validated by analysis; Will & Fienup 2019, submitted)
- A sun***shade*** that is larger but simpler than the JWST sun***shield*** (three layers instead of JWST's five, relaxed requirements on layer positioning after deployment)
- A field-of-regard that covers most of the sky (LUVOIR can point to within 45° of the Sun), greatly enhancing target of opportunity, exoplanet, and solar system observations
- Moving target capability with tracking speed of 60 mas/sec (2x faster than JWST)
- HDI: A near-UV to near-IR imager covering 200–2500 nm, diffraction limited and Nyquist sampled at 500 nm, with high precision astrometry capability
- ECLIPS: A high-contrast coronagraph with imaging cameras and integral field spectrographs spanning 200–2000 nm, capable of directly observing a wide range of exoplanets and obtaining spectra of their atmospheres
- LUMOS: A far-UV imager and multi-resolution, multi-object spectrograph covering 100–1000 nm, capable of simultaneous observations of up to hundreds of sources
- POLLUX: A high-resolution, point-source UV spectropolarimeter covering 100–400 nm, designed for LUVOIR-A. This instrument study was contributed by a consortium of European institutions, with support from the French Space Agency

A transformative facility like LUVOIR with its large aperture and need for high-contrast observations of Earth-like exoplanets requires new approaches to designing and realizing an observatory. Far more than previous space telescopes, LUVOIR must be considered as an integrated system and was designed for adaptability:

- Scaleable architecture to leverage a rapidly changing launch vehicle landscape

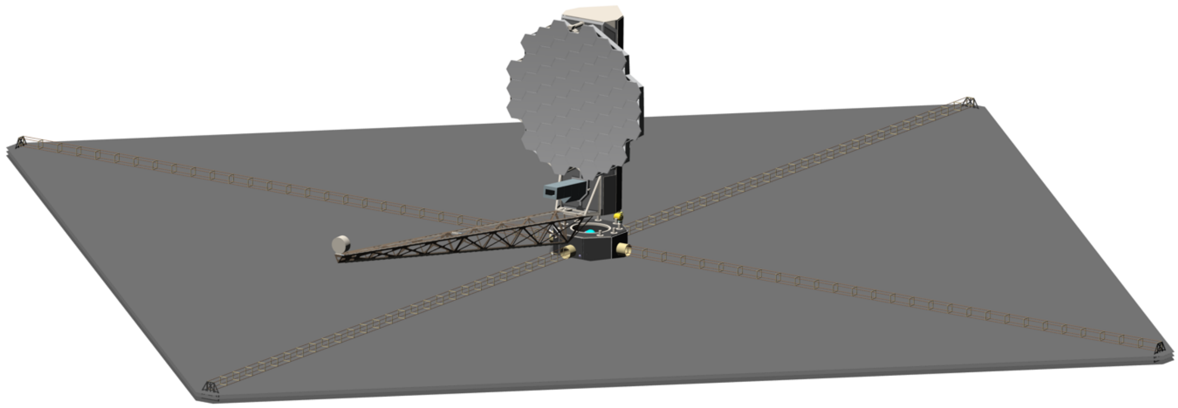

***Figure 5:*** *The LUVOIR-B observatory, with an 8-m diameter off-axis primary mirror and three instruments. Deployment and pointing animation at [https://asd.gsfc.nasa.gov/luvoir/design/](https://asd.gsfc.nasa.gov/luvoir/design/). Credit: A. Jones (NASA GSFC)*

- Modular design to ease on-orbit servicing and integration & testing on the ground
- Several layers of active wavefront control on the telescopes and within instruments to relax constraints on hardware precision and on-the-ground verification
- Minimization and isolation of vibrations and thermal disturbances throughout the observatory

## Technology Drivers

Revolutionary science goals require a technologically challenging observatory. The large LUVOIR apertures demanded by our sensitivity and spatial resolution goals must be segmented and deployable to fit within a launch vehicle. Fortunately, the JWST has paved the way in this area. The LUVOIR design builds off huge investments in deployable, segmented space telescope technology.

LUVOIR's most technically challenging observational goal is the extreme starlight suppression needed to directly observe Earth-like exoplanets around Sun-like stars ($10^{-10}$ raw contrast). There are two basic instruments to do this: coronagraphs and starshades. For telescopes as large as LUVOIR, coronagraphs are the most efficient means to search for and study a large number of exoplanets over a wide wavelength range. The highest coronagraph contrast measured to date in broadband light ($6 \times 10^{-10}$ with an unobscured aperture) was demonstrated in testbeds at JPL (Trauger et al. 2012). Therefore, coronagraph performance must be improved in several ways for LUVOIR to achieve its goal of directly studying rocky exoplanets in the habitable zones of Sun-like stars.

As part of addressing this challenge, NASA has embarked on several starlight suppression technology programs. The most important current effort is the WFIRST

Coronagraph Instrument (CGI) technology demonstration program, which is developing a high-performance coronagraph coupled to a complex, obscured telescope aperture. A coronagraph's performance is directly linked to stability of the wavefront of light entering it. The CGI program has made great strides in developing technologies and algorithms to stabilize the wavefront coming from the telescope (low-order wavefront sensors, deformable mirrors).

The LUVOIR coronagraphs must achieve about another order of magnitude improvement in contrast beyond the current record for obscured apertures ($2 \times 10^{-9}$), achieved through the CGI program[2]. To do this, the LUVOIR observatory was designed with wavefront stability, sensing, and control in mind at all times. The LUVOIR Team has assessed the technological maturity of each ***piece*** of the starlight suppression system; all are currently at Technology Readiness Level (TRL) 3 or higher.

The major remaining challenge is to show that the whole design works together as a ***system*** to provide the needed final coronagraph performance. In 2017, NASA funded two one-year industry studies of ultra-stable opto-mechanical systems. Results from these studies are available on-line[3] and will be made available to the Astro2020 panels. Proposals for follow-on two-year technology maturation contracts are under review. These will advance the technological maturity of stable, segmented telescopes, and will evaluate the end-to-end performance that can be achieved. In combination with further planned coronagraph development, these efforts will advance the maturity of LUVOIR's whole starlight suppression system to TRL 3 or higher.

The LUVOIR Team's technology assessments and Pre-Phase A plan to mature all technologies to TRL 6 by the start of Phase A will appear in Chapter 11 of the Final Report. The Pre-Phase A plan includes a 5-year schedule with funded schedule reserves and an estimated cost with margin.

## Organization, Partnerships, and Current Status

At the present time, LUVOIR is envisaged as a NASA-led, industry-supported large project. The LUVOIR Team also anticipates participation by international space agencies, 11 of which have been represented during the study by non-voting members of the STDT[4].

## Schedule

The LUVOIR development schedule extensively draws on lessons learned from other NASA strategic missions. At a high level, three major causes of schedule slips and

[2] https://exoplanets.nasa.gov/internal_resources/1200/
[3] Search on "SMTP" at http://www.astrostrategictech.us
[4] List of international representatives at https://asd.gsfc.nasa.gov/luvoir/team/

their attendant cost overruns are immature technologies, insufficiently detailed system-level designs early in development, and late changes to requirements. These lead to re-designs that force the "marching army" to march in place for a time. The LUVOIR Team has put extensive thought into how to avoid these pitfalls.

While the standard NASA mission development process functions well for missions of low or moderate complexity, the LUVOIR Team believes that this process must evolve to manage the increased complexity of the next generation of large strategic missions. Most importantly, key technologies should be matured to a higher level (TRL 6) ***before*** the start of the mission (during Pre-Phase A). However, the technology development should still be focused upon a specific architecture. In addition, for complex observatories, it is critical to begin development of all major components (including the spacecraft) early and develop them in parallel.

Keeping these principles in mind, the LUVOIR Team created detailed development schedules for both LUVOIR-A and B, which appear in Chapter 12 of the Final Report. The Large Mission Concept Study teams were instructed by NASA to assume a Phase A start in Jan 2025 and create schedules extending to the end of Phase D (end of commissioning). The launch dates are Nov 2039 for LUVOIR-A and July 2039 for LUVOIR-B. Including commissioning, the total schedule durations are 15.6 years for LUVOIR-A and 15.3 years for LUVOIR-B. The fact that the schedules for both LUVOIR concepts are so similar may be surprising. However, many of the components of LUVOIR-A and -B are nearly identical in size and complexity, and therefore have basically the same required development time.

## Cost Estimates

The LUVOIR mission represents a transformative vision for the future. Bold science goals that will revolutionize humanity's understanding of their place in the universe require ambitious capabilities and technology. Nevertheless, the LUVOIR Team and NASA both believe that a balanced portfolio of missions of different scales is critical for the health of the scientific community and are keenly aware that time and resources for new missions are not inexhaustible.

NASA and the community must work together to find solutions that enable the capabilities needed by current and future scientists at a reasonable cost-benefit ratio. While the large amount of time and expense needed to realize a strategic mission may be warranted, long schedule delays and attendant cost overruns are not. It is difficult to accurately cost large mission concepts at an early stage of development, but the LUVOIR Team has put a great deal of thought and effort into enabling increased cost fidelity and mitigating cost and schedule risks (Chapter 12 of the Final Report). The key features of our effort are:

- Greatly increased design and engineering detail for the concepts
- A thorough technology development plan, including schedule and estimated costs, that matures technologies earlier in mission formulation
- Mitigation of launch vehicle risk via a scalable mission architecture
- Conservative engineering margins (more conservative than required by GSFC)

With this information in hand, GSFC has performed cost estimates for both LUVOIR concepts using two different internal models: The Resource Analysis Office (RAO) tool and the Cost Estimating, Modeling, and Analysis Office (CEMA) tool. These estimates are currently being reviewed and validated by the LUVOIR Team, but it is clear that both concepts fall into the "Large" space mission category (>$1.5B in fiscal-year 2020 dollars). We expect feedback from an expert group organized by NASA Headquarters to perform cost and technical credibility analysis for all four large mission concept studies (the Large Mission Concept Independent Assessment Team) on July 17. All LUVOIR cost estimates, with associated explanations, will appear in the Final Report.

A few important points may be made now: mission cost estimate analysis shows that completely executing the technology development plan before Phase A results in total mission cost savings that ***greatly*** exceed the cost of the plan. The Final Report will contain extensive discussion of improvements to project management, procurement, and funding procedures; building on the recommendations in Bitten et al. (2019) to present a programmatic path towards realizing future Astrophysics flagship missions. As much as the technology development plan, such improvements are ***enabling*** for LUVOIR. Discussions of alternate funding models and better approaches to large project management appear in the APC White Papers by J. Crooke and J. Hylan.

In sum, LUVOIR is an ambitious mission concept that will provide the most science for the most scientists, but will require careful attention and new ways of executing large missions to make it feasible in terms of cost. However, the LUVOIR Team believes that this can be done, and has worked to develop plans to effectively realize our vision for a revolutionary observatory while maintaining a balanced portfolio of Astrophysics missions. We further believe that LUVOIR's compelling science goals will excite the scientific community, the public, and the stakeholders in government, leading to sustained and possibly increased support for space astrophysics in the US.

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