The Large UV/Optical/Infrared Surveyor (LUVOIR): Decadal Mission Concept Study Update

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***Abstract*—In preparation for the 2020 Decadal Survey in Astronomy and Astrophysics, NASA commissioned the study of four large mission concepts: the Large UV/Optical/Infrared Surveyor (LUVOIR), the Habitable Exoplanet Imager (HabEx), the far-infrared surveyor Origins Space Telescope (OST), and the X-ray surveyor Lynx. The LUVOIR Science and Technology Definition Team (STDT) has identified a broad range of science objectives for LUVOIR that include the direct imaging and spectral characterization of habitable exoplanets around sun-like stars, the study of galaxy formation and evolution, the exchange of matter between galaxies, star and planet formation, and the remote sensing of Solar System objects. The LUVOIR Study Office, located at NASA's Goddard Space Flight Center (GSFC), is developing two mission concepts to achieve the science objectives. LUVOIR-A is a 15-m segmented-aperture observatory that would be launched in an 8.4-m extended fairing on the Space Launch System (SLS) Block 2 configuration. LUVOIR-B is an 8-m unobscured segmented aperture telescope that fits in a smaller, conventional 5-m fairing, but still requires the lift capacity of the SLS Block 1B Cargo vehicle. Both concepts include a suite of serviceable instruments: the *Extreme Coronagraph for Living Planetary Systems* (ECLIPS), an optical / near-infrared coronagraph capable of delivering 10^{-10} contrast at inner working angles as small as 2 λ/D; the *LUVOIR UV Multi-object Spectrograph* (LUMOS), which will provide low- and medium-resolution UV (100 – 400 nm) multi-object imaging spectroscopy in addition to far-UV imaging; the *High Definition Imager* (HDI), a high-resolution wide-field-of-view NUV-Optical-NIR imager. LUVOIR-A also has a fourth instrument, *Pollux*, a high-resolution UV spectro-polarimeter being contributed by Centre National d'Etudes Spatiales (CNES). This paper provides an overview of the LUVIOR science objectives, design drivers, and mission concepts.**

TABLE OF CONTENTS

1. INTRODUCTION

The Astrophysics Division of NASA's Science Mission Directorate commissioned the study of four large mission concepts for consideration by the 2020 Decadal Study [1]: the Large UV/Optical/Infrared Surveyor (LUVOIR) [2][3], the Habitable Exoplanet Imager (HabEx) [4], the Origins Space Telescope (OST, formerly the Far-Infrared Surveyor) [5], and Lynx (formerly the X-ray Surveyor) [6]. A Science and Technology Definition Team (STDT) leads each study, and is tasked with defining a compelling science case and developing mission architectures capable of achieving that science case. In this paper, we present two mission concepts being studied by the LUVOIR STDT and Study Office.

The paper is organized as follows: The remainder of Section 1 briefly outlines the LUVOIR science case, and discusses the design philosophy adopted by the LUVOIR STDT and Study Office. Section 2 provides an overview of the LUVOIR mission architecture, while Sections 3 and 4 discuss the LUVOIR payload and spacecraft elements, respectively. Section 6 lays out the schedule for the remainder of the LUVOIR study, and concludes the paper.

Portions of this text appeared in the LUVOIR Interim Report [2], released by the LUVOIR Science and Technology Definition Team in August of 2018. This paper expands on the interim report by including new material pertaining to the LUVOIR-B architecture.

Science with LUVOIR

The LUVOIR STDT has identified a wide range of compelling science objectives that appeal to a broad section of the astrophysics community. The science objectives are organized along three main themes: cosmic origins, exoplanets, and the Solar System.

The cosmic origins science theme is enabled by a breadth of observational capabilities at unprecedented sensitivity and resolution, and fundamentally addresses the question, "How did we come to be?" Observations will cover everything from large-scale cosmological structure, to galaxy formation, evolution, and interaction, to star and planetary formation mechanisms – all across a broad spectral range spanning the far-ultraviolet (FUV) to the near infrared (NIR).

The exoplanet science case seeks to answer the questions, "Are we alone?", and "Are we unique?", enabled by the ability to directly image habitable exoplanets around sun-like stars, and spectroscopically characterize their atmospheres. Through a statistical survey of hundreds of planetary systems, LUVOIR will not just be able to determine *if* life is present, but also *how common* life might be throughout the galaxy. LUVOIR is not limited to just Earth-like planets, however. During the exoEarth survey, hundreds of other planets would be observed and characterized, allowing for a campaign of comparative planetology.

The same capabilities that enable the cosmic origins and exoplanet science would also enable groundbreaking observations within our own solar system. LUVOIR will achieve similar resolutions as planetary probe missions currently do, turning these once-in-a-lifetime science campaigns into routine studies. LUVOIR would also enable new observations of comets, asteroids, and Kuiper belt objects.

These compelling science objectives define a set of high-level mission capabilities: sensitivity, resolution, flexibility, high-contrast imaging, and mission duration. The LUVOIR Study team has used these capabilities to define a set of mission functional requirements that include (but are not limited to): a large (8-15 meter) aperture; broad wavelength sensitivity (~100 nm – ~2.5 μm); a suite of upgradeable instruments with imaging, spectroscopic, and high-contrast capabilities; and a long mission lifetime enabled through serviceability.

The science objectives, and specifically the high-contrast imaging capability, also drive the most difficult technical challenges of the LUVOIR concepts: picometer-level wavefront stability; large, low-noise, high-sensitivity focal planes; and highly reflective, uniform mirror coatings. For a more detailed discussion of these technology needs and their development, the reader is referred to Chapter 11 of [2], and for a more thorough discussion of the science investigations, the reader is referred to Chapters 2-7 of the same.

Why Two Architectures?

The Decadal Survey will recommend NASA's priorities in the next decade, based on the inputs it receives from the scientific community. However, when doing so, it will be faced with a number of uncertainties, such as future budgets, the availability and capability of launch vehicles, and the as yet unknown discoveries of both the James Webb Space Telescope (JWST) and the Wide-field Infrared Survey Telescope (WFIRST). The LUVOIR Study Team has therefore chosen to study two architectures that bracket a range of scientific capability, cost, and risk, allowing the Decadal Survey to evaluate LUVOIR's science yield as a function of these parameters. LUVOIR-A is a 15-m segmented, on-axis telescope, while LUVOIR-B is an 8-m segmented, off-axis (or unobscured) telescope.

The STDT initially laid out a requirement for LUVOIR-B that it should fit into a "conventional" heavy-lift launch vehicle, whereas LUVOIR-A was designed specifically to use the full capabilities of NASA's planned Space Launch System (SLS) Block 2 vehicle with an 8.4-m x 27.4-m fairing [7]. The LUVOIR-B architecture would reduce overall mission cost and risk should the SLS Block 2 vehicle be developed too late to be used by LUVOIR, or not achieve the current expected performance. By "conventional", the team implied a launch vehicle similar to the existing United Launch Alliance Delta IV-Heavy vehicle with a 5-m x 19.8-m fairing, and a lift capability to the second Sun-Earth Lagrange point (SEL2) of ~10,000 kg. However, after additional engineering design work, it is clear that even LUVOIR-B will require a lift capacity greater than ~15,000 kg, although volumetrically it still fits within the smaller, 5-m-class fairing.

Stability as a Design Driver

A key LUVOIR science goal is to directly image and characterize earth-like planets around sun-like stars. This requires a high-contrast coronagraph instrument, capable of suppressing the light from a host star so that the faint reflected light from orbiting planets might be seen. The required contrast ratio between host stars and earth-like planets is ~10^{-10}. It has been shown that achieving such contrast with a coronagraph requires an end-to-end optical wavefront stability on the order of 10s of picometers per wavefront control step. This is particularly true at the spatial frequencies that correspond to the region over the focal plane where 10^{-10} contrast is desired. Generally speaking, low-order aberrations, such as coma and astigmatism, are less critical than mid-spatial frequency wavefront errors caused by segment-to-segment misalignments. This unprecedented stability requirement drives almost every aspect of the LUVOIR architecture, and has led to a three-tiered approach.

Wavefront Stability through Design—To achieve wavefront stability, one should first design a system that is as stable as possible. Thermal stability is achieved using materials with near-zero coefficient of thermal expansion (CTE) at the desired operating temperature (in this case, 270 K) such as Corning ULE or Schott Zerodur glass for mirror segments and tuned composites for structures. These materials are coupled with milli-Kelvin-level thermal sensing and control of the mirrors, structures, and interfaces.

Dynamic stability is achieved via stiff structures and mirrors, passive isolation at disturbance sources, and active vibration isolation between the spacecraft (where most disturbance sources exist) and the payload (where wavefront stability is critical). The vibration isolation and precision pointing system (VIPPS) uses non-contact voice coil actuators to physically decouple the payload from the spacecraft and control relative attitude and translation degrees of freedom between the two elements.

Wavefront Stability through Control—After minimizing system instability through design, it is necessary to sense and control any remaining instability. The faster this control loop can run, the shorter the period of time the system must maintain wavefront stability at the picometers level.

Current methods of wavefront sensing and control, such as low-order wavefront sensing and phase retrieval, typically use photons from the target star that have traversed the optical system to estimate the wavefront of that optical system. However, when observing dim target stars, it can take 10s to 100s of minutes to collect enough photons to generate a wavefront estimate of adequate signal to noise ratio. Techniques such as low-order wavefront sensing are also limited in the spatial frequency content that can be estimated.

Onboard metrology systems, such as segment edge sensors and/or laser metrology systems can be used to significantly reduce the control step time for critical spatial frequencies since they do not rely on stellar photon rates.

Another alternative is to borrow a technique from ground-based observatories and use a bright, artificial guide star as a source for low-order or out-of-band wavefront sensors. A CubeSat with a bright laser or LED beacon flying a few hundred kilometers in front of the observatory may be sufficient.

All of these techniques can be used to reduce the amount of time between control steps, thus reducing the amount of time over which the system must be stable at the picometers level.

Wavefront Stability through Tolerance—The final tier involves continuing to develop new coronagraph architectures that are designed to be less sensitive to wavefront error in general. Additional spatial filtering and post-processing techniques may be able to relax wavefront sensitivities from 10s of picometers to 100s of picometers or even nanometers. While several of these approaches show promise, they are still very early in development and require further study.

2. LUVOIR MISSION OVERVIEW

The LUVOIR Mission consists of three segments: the observatory segment, the ground segment, and the launch segment.

Observatory Segment

As discussed earlier, the observatory segment has two variants. LUVOIR-A is a 15-m on-axis segmented telescope with four instruments, and LUVOIR-B is an 8-m off-axis segmented telescope with three instruments. The observatory segment consists of the payload element and the spacecraft element. Later sections of this paper discusses these elements for each architecture in more detail. Here, we briefly discuss the common, mission-level design features that are shared by both LUVOIR variants.

The LUVOIR observatory is a deployable space telescope, similar in concept and design to JWST. Whereas JWST is a passively-cooled cryogenic, near- and mid-infrared observatory, LUVOIR is an ultraviolet-optical-infrared observatory that is actively controlled to an operating temperature of 270 K. The observatory will occupy a quasi-halo orbit about the sun-earth 2nd Lagrange point (SEL2). From this orbit, LUVOIR will have access to the entire anti-sun hemisphere, as well as the sunward portion of the sky up to 45° from the sun-earth axis for time-critical observations.

The LUVOIR observatory and science program are designed with a 5-year mission lifetime requirement. However, both LUVOIR architectures are designed to be serviceable and upgradeable, including the ability to refuel the spacecraft, replace key spacecraft systems such as control moment gyroscopes and solar panels, and replace or upgrade any of the science instruments, as was done for the Hubble Space Telescope. Thus, beyond the 5-year lifetime requirement on all observatory elements, there is a 10-year lifetime goal for all serviceable systems, and a 25-year lifetime goal for all non-serviceable systems.

Table 2 summarizes the mass allocation and Table 1 summarizes the power budget for the observatory segment for both LUVOIR architectures.

Table 2 – Mass allocation for the LUVOIR Observatory Segment.

System / Subsystem	Current Best Estimate Mass [kg]		Mass Growth Allowance	Maximum Expected Value [kg]		Margin	Maximum Permissible Value [kg]	
	LUVOIR-A	LUVOIR-B		LUVOIR-A	LUVOIR-B		LUVOIR-A	LUVOIR-B
Payload Element	***17,490***	***7,835***	-	***23,600***	***10,654***	-	***31,467***	***14,205***
Optical Telescope Assembly	14,550	5,650	25.00%	19,400	7,533	25.00%	25,867	10,044
High Definition Imager	660	455	30.00%	943	650	25.00%	1,257	867
LUVOIR UV Multi-object Spectrograph	520	580	30.00%	743	829	25.00%	990	1,105
Extreme Coronagraph for Living Planetary Systems	750	750	30.00%	1,071	1,071	25.00%	1,429	1,429
Pollux	450	N/A	30.00%	643	N/A	25.00%	857	N/A
Payload Articulation System	560	400	30.00%	800	571	25.00%	1,067	762
Spacecraft Element	***5,720***	***2,085***	-	***8,171***	***2,979***	-	***10,895***	***3,971***
Spacecraft Bus	5,170	1,600	30.00%	7,386	2,286	25.00%	9,848	3,048
Sunshade	550	485	30.00%	786	693	25.00%	1,048	924
Propellant	***1,502***	***540***	***0.00%***	***1,502***	***540***	***25.00%***	***2,002***	***720***
Total:	**24,712**	**10,460**	-	**33,273**	**14,173**	-	**44,364**	**18,897**

Table 1 – Power allocation for the LUVOIR Observatory Segment.

System / Subsystem	Current Best Estimate Mass [W]		Power Growth Allowance	Maximum Expected Value [W]		Margin	Maximum Permissible Value [W]	
	LUVOIR-A	LUVOIR-B		LUVOIR-A	LUVOIR-B		LUVOIR-A	LUVOIR-B
Payload Element	***12,745***	***8,060***	-	***21,242***	***13,433***	-	***28,322***	***17,911***
Optical Telescope Assembly	9,350	5,140	40.00%	15,583	8,567	25.00%	20,778	11,422
High Definition Imager	375	350	40.00%	625	583	25.00%	833	778
LUVOIR UV Multi-object Spectrograph	960	960	40.00%	1,600	1,600	25.00%	2,133	2,133
Extreme Coronagraph for Living Planetary Systems	1,450	1,450	40.00%	2,417	2,417	25.00%	3,222	3,222
Pollux	450	N/A	40.00%	750	N/A	25.00%	1,000	N/A
Payload Articulation System	160	160	40.00%	267	267	25.00%	356	356
Spacecraft Element	***820***	***820***	-	***1,367***	***1,367***	-	***1,822***	***1,822***
Spacecraft Bus	820	820	40.00%	1,367	1,367	25.00%	1,822	1,822
Sunshade	0	0	40.00%	0	0	25.00%	0	0
Total:	**13,565**	**8,880**	-	**22,608**	**14,800**	-	**30,144**	**19,733**

Ground Segment

The ground segment for both LUVOIR variants is similar. It consists of a minimum of two ground stations that will communicate with the observatory segment via Ka-band (for science data downlink) and S-band (for telemetry, tracking, and control). A third ground station is optional, but would increase operational robustness.

Primary and backup mission operations centers will be responsible for critical observatory operations including orbit determination, telemetry and commanding, integrated trending, and mission planning. Similarly, a science operations center will be responsible for all observatory science operations, including observation scheduling, data processing and archiving, science data user support, and coordinating the general observer program.

Launch Segment

Determining a suitable launch vehicle for LUVOIR is complicated by both the long time horizon for a likely LUVOIR launch date (mid-to-late 2030s), as well as the current rapid growth and flux in the launch vehicle market. While NASA develops its Space Launch System crew and cargo vehicles, the commercial sector continues to advance an array of vehicles with evolving capabilities. Perhaps the only thing that is certain is that the launch-vehicle landscape will look very different in 10 years than it does today. Given this uncertainty, the LUVOIR architecture is designed to be scalable to fit whichever launch vehicles may be available.

3. THE LUVOIR PAYLOAD ELEMENT

The payload element for each architecture consists of several systems: the optical telescope assembly, the individual science instruments, and the payload articulation system.

Optical Telescope Assembly

Optical Design—The optical design for each LUVOIR architecture uses a three-mirror anastigmat (TMA) configuration, with a primary mirror, secondary mirror, and tertiary mirror correcting optical aberrations. A fourth fast-steering mirror, located at the real exit pupil of the TMA, allows for fine pointing control and jitter rejection. The primary mirror for both architectures is a deployable segmented design similar to JWST. Individual segments are continuously controlled in six rigid body degrees of freedom to form a uniform optical surface. Both designs provide diffraction-limited performance at a wavelength of 500 nm, and use an enhanced aluminum coating to provide broadband performance between 100 nm and 2.5 μm [8].

The LUVOIR-A design has a primary mirror that is 15 meters in diameter, with an "on-axis" secondary mirror. We note that we use the term "on-axis" to denote that the secondary mirror physically obscures part of the primary mirror, even though the actual optical design is slightly off-axis in field. Figure 1 shows an optical ray trace of the LUVOIR-A design, and the pupil geometry with dimensions.

The LUVOIR-B design has a primary mirror that is 8 meters in diameter, with an "off-axis" secondary mirror, i.e. the primary mirror remains unobscured by the secondary mirror. Figure 2 shows an optical ray trace of the LUVOIR-B design, and the pupil geometry with dimensions.

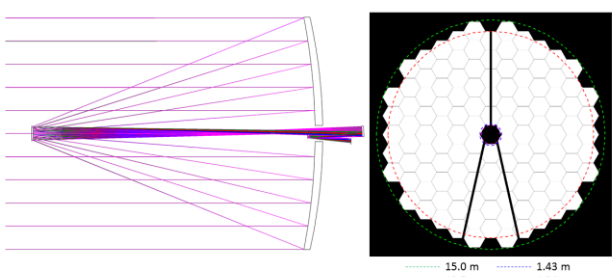

Figure 1 – (Left) Ray trace showing the LUVOIR-A TMA optical design. (Right) The LUVOIR-A pupil, with several diameters of interest labeled.

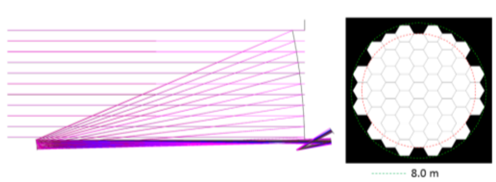

Figure 2 – (Left) Ray trace showing the LUVOIR-B off-axis TMA optical design. (Right) The LUVOIR-B pupil, with diameters of interest labeled.

Mechanical Design—The mechanical design for each LUVOIR architecture's optical telescope focused on maximizing the primary mirror area that could fit inside of the respective launch vehicle fairing while minimizing deployment complexity. Each design uses the same "wing-fold" concept as JWST to wrap the primary mirror around the central instrument column, conforming to the cylindrical shape of the fairing. LUVOIR-A has two hinge lines on each side of the primary mirror, while LUVOIR-B has three. More hinge lines allows the stowed primary mirror to more closely approximate a cylinder, allowing for more efficient use of the fairing volume, but at the expense of additional deployment mechanisms.

The secondary mirror must also be deployed from the stowed configuration, and here the two LUVOIR architectures differ significantly. LUVOIR-A uses a similar design as JWST, with the secondary mirror folding up and behind the primary mirror. Due to the large separation distance between the primary and secondary mirror, multiple hinges in each of the support struts are necessary. Figure 3 shows the LUVOIR-A payload in both the stowed and deployed configuration.

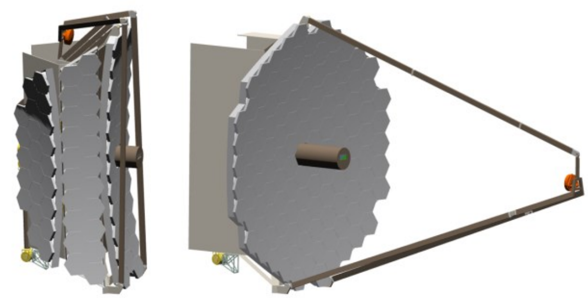

Figure 3 – (Left) The LUVOIR-A payload in its stowed configuration. Two hinge lines on either side of the primary mirror fold the mirror "wings" back for launch. The secondary mirror support structure folds up and behind the primary mirror. (Right) The deployed LUVOIR-A payload. In addition to the primary and secondary mirror deployment, the aft-optics structure deploys at the center of the primary mirror, and radiator panels on each side of and the top of the instrument column deploy for better cold-sink views.

A different approach is necessary to deploy the LUVOIR-B secondary mirror and support structure to a position that would not obscure the primary mirror. Instead of relying on multiple, thin support struts to hold the secondary mirror, as is done on LUVOIR-A, a single, robust truss structure is used. Three flat panels unfold and latch together to form a triangular cross-section beam. Figure 4 show the LUVOIR-B payload in both the stowed and deployed configuration.

The aft-optics system (AOS) on each architecture consists of the tertiary mirror, fast steering mirror, and associated support structure. A portion of the AOS deploys in front of the primary mirror to position a field-stop aperture at the internal focus of each TMA design.

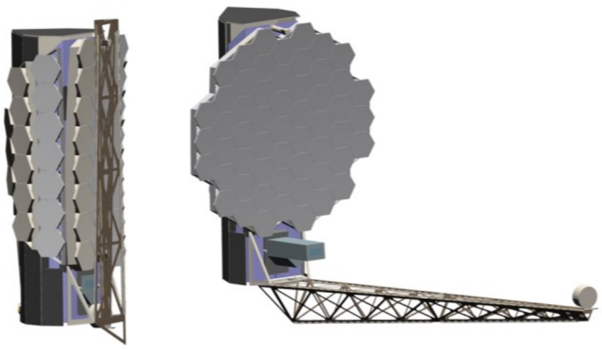

Figure 4 – (Left) The LUVOIR-B payload in its stowed configuration. Three hinge lines on either side of the primary mirror fold the mirror "wings" back for launch. The secondary mirror support structure folds up into a flat panel in front of the primary mirror. The panel unfolds along two hinges to create a triangular beam (right). In addition to the primary and secondary mirror deployment, the aft-optics structure deploys at the base of the primary mirror.

Both LUVOIR architectures use a backplane support frame (BSF) as the primary metering structure for the entire payload. The BSF provides structural support to the primary mirror, secondary mirror support structure, and aft-optics system – holding all three optical elements of the telescope in alignment with one another. The BSF also provides mounting interfaces and servicing infrastructure for the science instrument modules.

Thermal Design—The optical telescope assembly for both LUVOIR architectures is actively controlled to 270 K through the use of heaters and passive thermal isolation. This operating temperature was chosen as a compromise between operating as cold as possible to enable science in near-infrared bands, while operating warm enough to take advantage of numerous material properties to enable system stability. Molecular contamination due to outgassing from the composite structure also becomes challenging below ~260 K.

Thermal stability is critical to achieving the ultra-stable wavefronts necessary to enable the high-contrast exoplanet science. Thus, much of the optical telescope assembly is held to a thermal stability of +/- 1 mK, combined with materials that have near-zero CTE (e.g. ULE glass mirror segments, composite structures, etc.). Additional waste heat generated from the electronics is either used to actively heat the structure or is rejected to space via radiators on the BSF to mitigate any disturbances to the thermal stability.

Electrical Design—The electrical design of the optical telescope assembly consists of a centralized main electronics box (MEB) and power distribution unit (PDU), located in the BSF. The main electronics box provides control over most payload operations, including deployments, heater control, and housekeeping. The MEB also routes data from the science instruments to the spacecraft for downlink. The PDU takes in 120-v power from the spacecraft and steps it down to 28-v for distribution to payload systems. The PDU also routes 120-v power directly from the spacecraft to the piezo-electric actuators at each primary mirror segment assembly, for fine rigid body positioning of the segments.

Control of the individual primary mirror segment assemblies is distributed across the telescope. A mirror segment control electronics box is located with each mirror segment assembly (and the secondary mirror assembly), and controls that segment's heaters, actuators, position encoders, and edge sensors. Measurements from the edge sensors on each segment are collected by data routers positioned on each primary mirror "wing", and sent directly to a control system processor located within the coronagraph (discussed later - the control system processor is responsible for coordinating all aspects of the active control systems on LUVOIR to maintain wavefront stability). Figure 5 shows a block diagram of the LUVOIR-B payload electrical architecture.

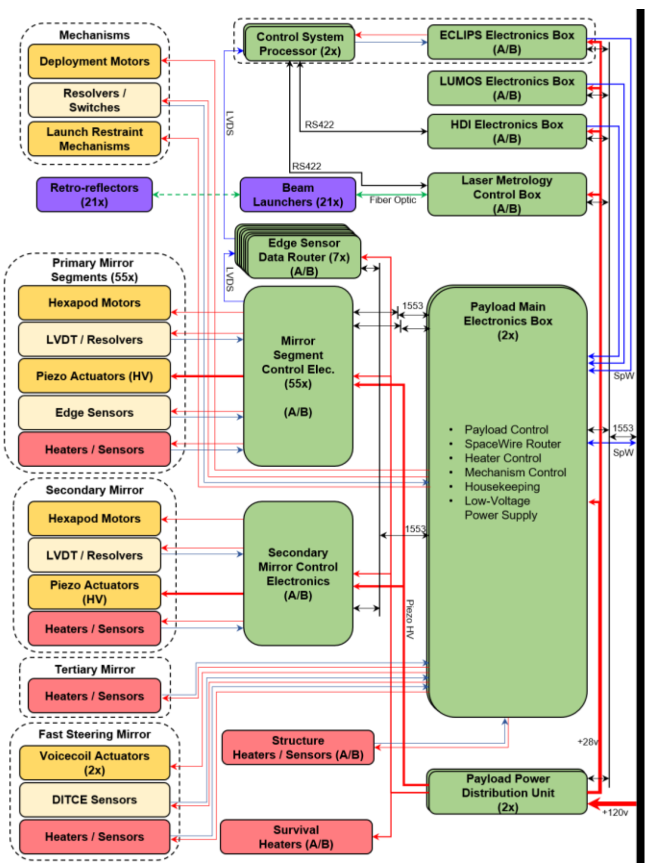

Figure 5 – The LUVOIR-B payload electrical architecture. Power (+120 v) and data (SpaceWire, 1553) interfaces from the spacecraft are at the right. Board-level redundancy is denoted by "(A/B)", and box-level redundancy is denoted by "(2x)". Redundant and cross-strapped connections are not shown for clarity. The LUVOIR-A electrical architectural is similar, save an additional instrument (Pollux), and different segment count (120 vs. 55).

High Definition Imager (HDI)

The High Definition Imager (HDI) is the primary imaging instrument for LUVOIR, providing wide-field of view, high resolution, UV-optical-infrared imaging capabilities. The instrument also serves as the fine guidance sensor for the observatory. HDI also has a precision astrometric mode, allowing it to not only monitor proper motions of distant stars and galaxies, but also to measure the masses of earth-like exoplanets as part of LUVOIR's exoplanet science campaign. Table 3 summarizes the key HDI performance requirements for both architectures.

Table 3 – HDI performance summary.

Parameter	HDI-A		HDI-B	
	UVIS	NIR	UVIS	NIR
Bandpass [μm]	0.200 – ~1.0	~1.0 – 2.1	0.200 – ~1.0	~1.0 – 2.1
Field of View [arcmin]	2.91 x 2.11	2.94 x 2.17	2.69 x 1.78	2.71 x 1.79
Platescale [mas/pixel]	3.44	6.88	6.45	12.89
RMS Wavefront Error [nm]	<35	<71	<35	<71
RMS Pointing Stability [1-σ mas]	0.43	0.86	0.81	1.61

Optical Design—The HDI optical design is driven by the requirement to perform broadband imaging between 200 nm and 2.1 μm over a wide, 2 arcmin x 3 arcmin field-of-view. The instrument has two channels: the ultraviolet-visible (UVIS) channel operating between 200 nm and ~1000 nm is Nyquist sampled at 500 nm, and the near-infrared (NIR) channel operating between ~1000 nm and 2.1 μm is Nyquist sampled at 1000 nm. Both channels share the same on-sky field-of-view. Each channel has a separate filter wheel assembly allowing for a wide assortment of spectral filters: up to 41 in the UVIS channel, and 26 in the NIR channel. The UVIS channel also contains weak-lens and dispersed Hartmann sensor elements to facilitate the collection of image-based wavefront sensing data for observatory commissioning and alignment.

A channel select mechanism determines which channel is operating at any given time. The channel select mechanism has five elements:

1. NIR Transmissive: sends all light from the optical telescope to the NIR channel. This position also allows light from an internal calibration source to be directed into the UVIS channel.

2. UVIS Reflective: sends all light from the optical telescope to the UVIS channel. This position also allows light from an internal calibration source to be directed into the NIR channel.

3. 50/50 Beamsplitter: allows for simultaneous operation of both channels over the entire instrument bandpass, but at reduced throughput.

4. Dichroic Beamsplitter: allows for simultaneous operation of the UVIS channel between 400 nm and 800 nm, and the NIR channel between 800 nm and 1.6 μm.

5. Optimized UV Reflective: sends all of the light from the optical telescope into the UVIS channel, but emphasizes UV throughput over broadband operation.

Both versions of the instrument make use of freeform optics to simultaneously enable a wide field-of-view with well corrected optical performance in a compact package. Figure 6 shows ray traces for both HDI-A and HDI-B.

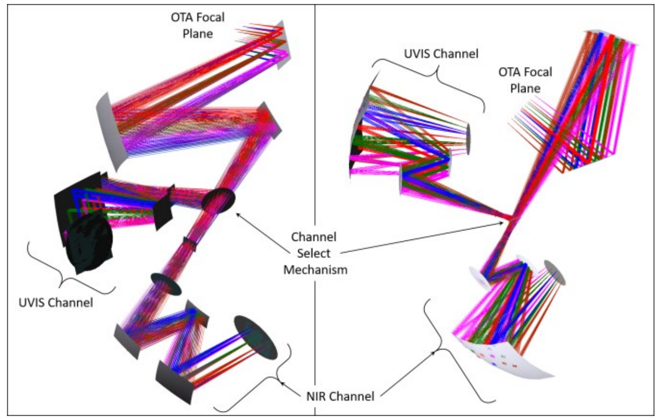

Figure 6 – Ray traces of HDI-A (left) and HDI-B (right).

Mechanical Design—The use of freeform optics in the design implies that the optical path for each channel does not necessarily lie in a single plane. This prevents the use of a single optical bench for mounting all of the hardware. Instead, the mechanical design for each instrument uses a frame to hold several panels and sub-benches for mounting the HDI optics and mechanisms. The frame interfaces to the BSF via three kinematic latches that can be remotely engaged and disengaged for servicing.

Thermal Design—For each instrument version, most of the structure and optics are actively heated to 270 K. The NIR optics are passively cooled to 170 K to reduce thermal backgrounds, and are isolated from the rest of the instrument via a thermal enclosure. The NIR focal plane is further cooled to a temperature of 100 K via passive radiators. Waste heat is transported to these radiators on the BSF via heat pipes.

Electrical Design—The HDI electrical system design is driven by the high data rates from the large focal planes. Front-end electronics are placed as close to the focal planes as possible to minimize harness length, and contain the necessary hardware to perform pixel processing such as co-adding and sampling-up-the-ramp.

Detectors—The focal plane size is driven by the field-of-view and Nyquist sampling requirements in each channel. While both HDI-A and HDI-B share the same requirements, the fact that LUVOIR-B's aperture diameter is ~53% that of LUVOIR-A means that HDI-B's focal plane is also about half the physical size of HDI-A. Table 4 summarizes the HDI detector specifications.

Table 4 – HDI Detector Specifications

Parameter	HDI-A		HDI-B	
	UVIS	NIR	UVIS	NIR
Detector Type	CMOS	HgCdTe	CMOS	HgCdTe
Pixel Size [μm]	6.5	10	6.5	10
Sensor Chip Assembly Size	8192 x 8192	4096 x 4096	8192 x 8192	4096 x 4096
Sensor Chip Assembly Tiling	6 x 4	6 x 4	3 x 2	3 x 2
Total Number of Pixels [Million]	1610.6	402.6	402.6	100.7
Nominal Data Rate [Mbps]	122.8	30.8	30.7	7.7

Another driving requirement for the focal planes is the need to perform fine guiding for the observatory. Small regions-of-interest can be defined around multiple, bright foreground stars and read-out at high speeds (up to 500 Hz) to provide a pointing signal to both the fast steering mirror and the VIPPS.

LUVOIR UV Multi-object Spectrograph (LUMOS)

LUMOS is the primary ultraviolet instrument on LUVOIR, operating at wavelengths as short as 100 nm. Its multi-object capability will allow it to investigate the flow of matter and energy between the intergalactic medium and circumgalactic media. Table 5 summarizes the LUMOS performance requirements.

Table 5 – LUMOS Performance Specifications

Parameter	LUMOS-A			LUMOS-B	
	MOS	Imager	High-Resolution	MOS/Imager	High-Resolution
Bandpass [nm]	100 - ~1000	100 - 200	100 - 200	100 - ~1000	100 - 200
Field-of-View [arcmin]	2 x 2	2 x 2	~1 arcsec	2 x 2	~1 arcsec
Average Angular Resolution [mas]	<25	12.6	N/A	<40	N/A

Optical Design—LUMOS is essentially three instruments in one: a spatially resolved multi-object spectrograph (MOS), an imager, and a high-resolution point-source spectrometer. LUMOS-A and LUMOS-B both have all of these capabilities, but take slightly different approaches to their implementation due to tighter instrument volume restrictions on LUVOIR-B.

On LUMOS-A, the three modes are implemented with three separate, independent channels, each with its own field-of-view. The 3 arcmin x 1.6 arcmin multi-object spectrograph field of view is defined by a micro-shutter array placed in the focal plane of the optical telescope assembly. Individual shutters can be opened or closed to define which targets in the field-of-view are to be investigated. The MOS channel contains a series of gratings that provide low- and medium-resolution in the far-UV (100 – 200 nm), near-UV (200 – 400 nm), and one medium resolution grating in the visible (400 – 1000 nm).

An adjacent 2 arcmin x 2 arcmin field-of-view defines the imaging channel, which contains a series of reflective filter wheel assemblies for defining the imaging bandpasses between 100 – 200 nm. A set of transmissive neutral density filters is also available to the imaging channel.

A special cross-over mode can be engaged in which the MOS channel field-of-view can be imaged onto the imaging channel detector. This allows for fine alignment of the MOS microshutters to targets of interest, as well as pre-screening of targets through the imaging channel neutral density filters for bright-object protection.

Finally, the high-resolution spectrometer channel is defined by a small (~1 arcsec) field-of-view adjacent to the imaging channel. This channel uses an echelle grating with a cross-disperser to achieve very high resolution (>100,000) in the far-UV (100 – 200 nm).

The LUMOS-B instrument shares many features with LUMOS-A, however due to volume restrictions on the smaller LUVOIR-B architecture, the imaging and MOS channels were combined into a single optical train with a shared 2 arcmin x 2 arcmin field-of-view. While imaging through the microshutter presents challenges due to vignetting and diffraction from the shutter edges, the overall science capability of the instrument is preserved.

For this design, multiple filter wheel assemblies are used – each containing either gratings, reflective filters, or both, to direct the beam path to the appropriate detector.

The high-resolution far-UV channel remains a separate, independent optical train with its own field-of-view.

Mechanical Design—To accommodate the multiple optical paths through each version of the instrument – including the cross-over mode on LUMOS-A, a truss structure is used to hold all of the opto-mechanical elements, as opposed to a traditional optical bench. For both instrument variations, the truss interfaces to the BSF through three kinematic latches that can be remotely engaged and disengaged for servicing.

Thermal Design—Contamination control is a primary concern for the LUMOS instrument, and thus it is designed to operate at a slightly warmer temperature than the surrounding structure and instruments (270 K). Heaters actively control the Far-UV components to 280 K to force contaminants to deposit on the colder surfaces surrounding the instrument and not the warmer mirrors in LUMOS itself. However, the inclusion of a near-UV MOS requires a 170 K environment to operate, and is therefore passively cooled and isolated from the 280 K components. Additionally, contamination control heaters on all mirrors, gratings, and detectors are sized to allow for infrequent on-orbit bake-outs to help evaporate any accumulated water vapor from the optics.

Electrical Design—In addition to the standard mechanism and detector control electronics, a dedicated electronics box is included to control the microshutter arrays. A high-voltage power supply is also included to drive both the calibration lamp sources, as well as the microchannel plate detectors.

Detectors—For both LUMOS instruments, micro-channel plate detectors are used for the far-UV bands, while UV-optimized (e.g. delta-doped) CMOS detectors are used for the near-UV and visible bands.

On LUMOS-A, the far-UV imaging channel detector is a single 200 mm × 200 mm microchannel plate with 20 μm spatial resolution, and employing a cross-strip anode readout system [9], which enhances detector lifetime. The imaging microchannel plate will have an open-face design with an opaque CsI photocathode that has high flight heritage on the HST Cosmic Origins Spectrograph instrument and numerous rocket missions [10][11][12][13].

The LUMOS-A far-UV MOS focal plane consists of a 2 × 2 array of 200 mm × 200 mm microchannel plates, with a 12 mm gap between the tiles. These microchannel plates again use a cross-strip anode readout, and have 20 µm spatial resolution. As the MOS will disperse spectra across this tiled array, each side of the array can be tailored to the specific wavelengths that will fall there. The blue side of the array will use the same open-faced CsI photocathodes as the imaging channel, while the red side of the array will use sealed-tube bialkali photocathodes [14][15].

On LUMOS-B, the combined MOS/Imager focal plane consists of a same 2 x 1 array of microchannel plates similar to those used on LUMOS-A.

Extreme Coronagraph for Living Planetary Systems (ECLIPS)

The scientific goals of the coronagraph instrument are organized around two key science themes:

(1) measuring the occurrence rate of biomarkers in the atmospheres of rocky planets orbiting in the habitable zone of their host stars, and

(2) studying the diversity of exoplanet systems.

The former science theme is significantly more stressing on the instrument and drives the ECLIPS design. The detectability of exoplanets in long coronagraph exposures depends on both the level of contrast achieved in the high-contrast region or "dark hole" of the focal plane, and on the throughput of the coronagraph at the apparent separation of the planets, expressed using the inner and outer working Angle (IWA and OWA, respectively) scalar metrics.

Table 6 summarizes the key performance requirements for the ECLIPS instrument.

Table 6 – ECLIPS Performance Summary

Parameters	ECLIPS-A and -B		
	UV	VIS	NIR
Bandpass [nm]	200 - 525	515 - 1030	1000 - 2000
IWA [λ/D]	3.5	3.5	2
OWA [λ/D]	64	64	64
Modes	Imaging	Imaging, IFS	Imaging, IFS
Spectral Resolution	N/A	140	70, 200

While there is currently no flight heritage for a coronagraph such as the one proposed for LUVOIR, the WFIRST Coronagraph Instrument (CGI) is the most similar coronagraph to ECLIPS, but is still under development. We expect that CGI development will help to advance the state-of-the-art in terms of how to successfully implement a coronagraph instrument on a space telescope, despite WFIRST and LUVOIR being very different observatories. The experience gained from integrating, testing, and operating a high-contrast coronagraph on-orbit will be invaluable.

Optical Design—The instrument is split into three channels that cover the following bandpasses: UV (200 to 525 nm), optical (515 nm to 1030 nm), and NIR (1.0 µm to 2.0 µm). These bands are achieved using a series of dichroics at the entrance of the instrument. Each channel is equipped with:

- two deformable mirrors (DMs) for wavefront control,
- a suite of coronagraph apodizing, occulting, and Lyot stop masks
- a Zernike wavefront sensor to be used as a low-order or out-of-band wavefront sensor (LOWFS, or OBWFS),
- a spectral filter wheel to select the instantaneous science bandpass for the channel, and
- separate science imagers and spectrographs.

Both versions of the ECLIPS are virtually identical, with the only significant difference being the type of coronagraph that is primarily implemented. On ECLIPS-A, an apodized pupil Lyot coronagraph (APLC) is prioritized to date, as it has shown the best overall performance with LUVOIR-A's obscured primary mirror. Apodizing, focal plane, and Lyot stop masks for a vector vortex coronagraph (VVC) are included as a secondary option for specific observations. On ECLIPS-B, the reverse is true: a VVC is prioritized as it has shown the best performance with LUVOIR-B's unobscured aperture. However, apodizing, focal plane, and Lyot stop masks for an APLC coronagraph are included as a secondary option for specific observations.

Mechanical Design—The mechanical design of the instrument uses two optical benches to hold the three channels. One bench holds the UV and visible channels on either side, while the second bench holds the NIR channel optics. A third "foot" bench holds the two optical benches at their base, and mounts to the BSF via three kinematic latches that can be remotely engaged and disengaged for servicing. This foot bench also holds the instrument electronics boxes. The two optical benches are further rigidized to one another via a central cylindrical column. Figure 7 shows the mechanical implementation of the ECLIPS-A instrument.

Thermal Design—The entire instrument is held at 270 ± 0.5 K. The UV and visible channel detectors are thermally isolated and passively cooled to 170 K, and the NIR channel detectors are further isolated and cooled to 100 K.

As a contamination control approach, all heaters are also sized to allow for infrequent bake-outs of the optical elements on-orbit, similar to the annealing approach used on HST detectors.

Electrical Design—In addition to the ECLIPS main electronics box, which controls most of the instrument mechanisms, data collection, and housekeeping operations, the instrument also includes the control system processor (CSP). The CSP is the central brain for all control systems on either LUVOIR architecture, including the primary mirror segment edge-sensors, piezo-electric actuators on the mirror segments and secondary mirror, and any other metrology that may be included. The CSP is responsible for autonomously executing the wavefront control algorithms required to dig the high-contrast dark hole. The CSP uses a hybrid architecture consisting of a central processing unit to handle overall algorithm execution and data I/O, and a battery of field programmable gate arrays to perform dedicated, computationally intensive tasks such as matrix inversions and fast Fourier transforms.

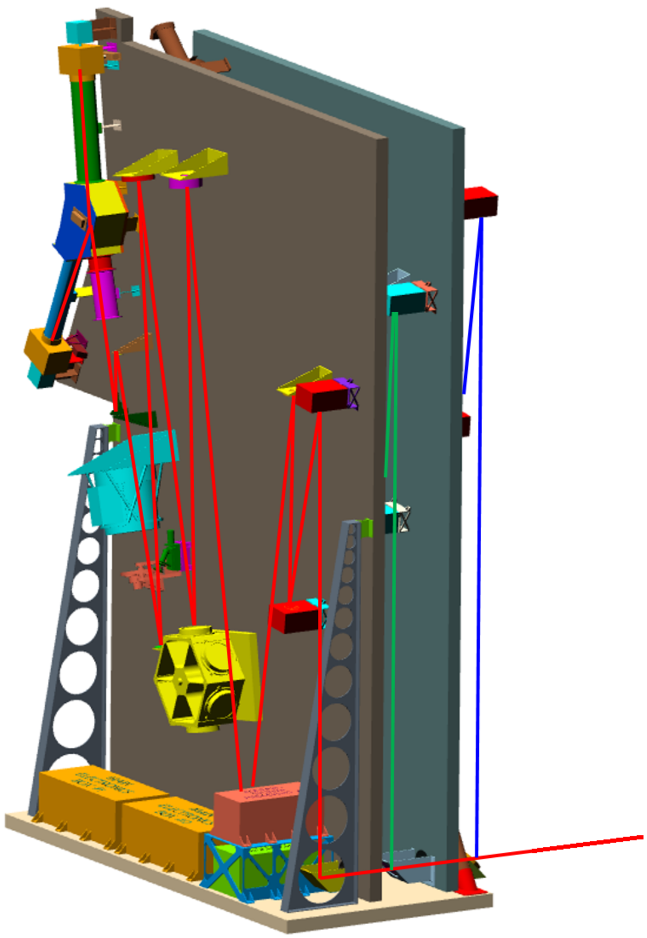

Figure 7 – ECLIPS-A opto-mechanical design, with colored-lines showing approximate ray path. Light enters from the OTA from the right, with the UV channel picked-off first (blue line), the VIS channel second (green line), and the NIR channel last (red line).

Detectors—In the UV and visible channels, electron multiplying CCD (EMCCD) devices will be used, with the UV channel devices being UV-optimized (e.g. via delta-doping) for better shortwave performance. Current devices are being developed and tested for the WFIRST coronagraph mission with 1k × 1k, 13 µm pixels. These 1k × 1k devices will be sufficient for the UV and visible channel imagers, however, to cover the field-of-view and spectral resolution of the visible channel IFS, a 4k × 4k device will be required.

The baseline technology for the NIR channel is the Teledyne HAWAII 4RG (H4RG) HgCdTe detector. Current devices have a format of 4k × 4k with 10 µm pixels. H4RGs are the baseline detector for the WFIRST wide-field instrument and are an evolution of H2RG detectors used on the JWST NIRCam instrument.

Pollux

The Pollux instrument is currently being studied by a consortium of European partners, led by the Centre national d'etudes spatiales (CNES). Although the Pollux instrument is a proof-of-concept demonstration of an instrument that would work with either LUVOIR architecture, the specific implementation being studied as the fourth instrument on the LUVOIR-A architecture.

Pollux is a UV spectropolarimeter that complements the LUMOS instrument in both capability and scientific objectives. It combines high-resolution (R > 120,000) spectroscopy in the far- and near-UV (~100 – 400 nm) with polarimetry.

The Pollux instrument study is still ongoing, and for more information regarding its science goals and design implementation, the reader is referred to [2][16][17].

Payload Articulation System

The payload articulation system has two key components: the gimbal arm, and the vibration isolation and precision pointing system (VIPPS).

Gimbal Arm—The gimbal arm is responsible for coarse pointing of the payload relative to the spacecraft. The purpose for pointing the payload independently of the spacecraft and sunshade is twofold.

First, by keeping the sunshade in a fixed orientation relative to the sun, the change in the thermal load on the sunshade is minimized. This creates a very stable thermal environment on the dark side of the sunshade. As the payload repoints, it will experience different view factors to the sunshade, but by keeping the profile on the dark side of the sunshade cold, and stable, the resulting thermal instability can be reduced.

The second purpose of the gimbal arm is to maintain alignment of the payload center of gravity with the center of pressure on the sunshade. This minimizes momentum build-up in the spacecraft attitude control system, reducing the operational overhead from momentum unloading.

VIPPS—The VIPPS "floats" the telescope and controls the payload attitude relative to the interface plane via six non-contact voicecoil actuators. The VIPPS effectively isolates any dynamic disturbances from the spacecraft attitude control system from transmitting to the payload and exciting resonances that contribute to wavefront instability. The VIPPS also provides fine pointing control of the payload during science observations [18][19].

While the VIPPS provides ideal mechanical isolation, power and data signals must still be transmitted between the payload and spacecraft. Using a 120-v bus for the electrical power system allows for fewer, smaller-gauge conductors to be used, minimizing the number of cables and cable stiffness that must bridge the non-contact gap. Similarly, by performing as much of the data-processing on the payload side as possible, the cabling requirements for data transfer between the payload and spacecraft are minimized.

4. THE LUVOIR SPACECRAFT ELEMENT

The spacecraft element for each architecture consists of the spacecraft bus and sunshade systems.

Spacecraft Bus

Structure—The spacecraft designs for both LUVOIR architectures is very similar, with LUVOIR-A's spacecraft being larger to support the larger payload. The bus is octagonal in shape, with a central cylindrical structure to serve as the load path between the payload and launch vehicle. Propulsion tanks are housed in the center of the cylinder, while other spacecraft subsystems are held by secondary structure surrounding the cylinder, which also keeps the systems easily accessible for servicing.

Attitude Control System (ACS)—The spacecraft is three-axis stabilized and inertially fixed, with the spacecraft axial vector parallel to the sun-spacecraft axis. The ACS is responsible for counteracting external disturbances (primarily solar pressure torques), as well as changing the yaw axis of the observatory and reacting against gimbal pitch changes during payload retargeting maneuvers.

The spacecraft ACS is also responsible for specific science observations that require pointing the entire observatory towards the sun, up to 45°.

The ACS sensor suite serves two functions: star trackers, gyroscopes, accelerometers, and coarse sun sensors determine the attitude and inertial position of the spacecraft relative to the sun, while proximity sensors on the VIPPS determine the relative attitude between the spacecraft and the payload. ACS actuators, consisting of four control moment gyroscopes (CMGs) and sixteen 5-lb. thrusters respond to the sensor suite to maintain the absolute attitude and inertial position of the spacecraft. The four CMGs are arranged to provide full three-axis stabilization with redundancy. The thrusters are arranged in two sets: the first is used during momentum dump maneuvers, the second is used for station-keeping and orbit maintenance.

Command & Data Handling (C&DH)—The C&DH system consists of a solid state recorder, a board-level computer for command and control, and dedicated controller boards for spacecraft deployment and gimbal mechanisms. To ensure the payload never sees direct sunlight, a separate ACS safe-hold processor takes over in the event of a C&DH system failure to maintain a safe attitude. Each instrument contains enough internal storage for two day's-worth of data. Therefore, the solid state recorder on the spacecraft only needs to act as a buffer for each downlink, and is sized to hold only a single downlink's worth of data.

Communications—The communications system uses Ka-band for data downlink and S-band for telemetry and housekeeping. While radio frequency provides sufficient margin for both LUVOIR architectures, optical communication would provide additional robustness and room for future growth. Should sufficient investment be made in additional optical ground stations, LUVOIR could easily make use of recent optical communication developments.

Electrical Power System—Both LUVOIR architectures use two roll-out solar arrays to supply electrical power to the observatory. The spacecraft supplies 120-v power directly to the payload, and separately steps power down to 28-v for local spacecraft subsystems. A 24 amp-hour battery provides power during launch and ascent.

LUVOIR is a Class A mission, and adopts an appropriate risk posture. All electrical system boards are side-A / side-B redundant or box-level redundant, all mechanisms have dual-windings, and all electrical power and data interfaces are either cross-strapped, redundant, or both.

Sunshade

A central component of the LUVOIR thermal management architecture is the deployable sunshade. The sunshade isolates the payload from solar thermal loads and provides a cold environment in which the payload can be thermally stabilized with active heaters, and in which system radiators have sufficient cold-sink temperatures.

Although the sunshade appears similar in concept and design to that of JWST, it differs in two important aspects. First, it is larger. While JWST's sunshield is tennis-court sized, the LUVOIR-A sunshade is closer in size to a football field, spanning nearly 80-m tip-to-tip, with LUVOIR-B's sunshade nearly 63-m tip-to-tip. And whereas JWST's sunshield is an extremely complex system of 5 thin layers that need to be precision deployed to tight tolerances on the angle and separation between the layers, LUVOIR's sunshade is simpler. A minimum of two sheets of single-layer insulation are needed to meet the thermal performance requirements, although three layers will likely be needed for redundancy against micrometeoroid strikes. The spacing and angle between these layers is not critical, so long as they do not touch.

The manner in which the sunshade is deployed also differs between LUVOIR and JWST. JWST uses two rigid pallets to hold the sunshield system. These pallets are stowed up around the telescope and instruments, cocooning the payload during launch and ascent. After launch, the JWST's pallets fold down, and port and starboard deployable booms pull the sunshield layers out from the pallet, before spreaders and tensioners fine-position the five layers. In contrast, LUVOIR will package the entire sunshade at the base of the spacecraft. Four deployable booms will pull the folded sunshade out in each of four directions: fore, aft, port, and starboard. The details of the deployment are still being worked by the Study Team, but we anticipate several advantages over JWST, as well as several new challenges. Advantages include a smaller relative mass and volume for the stowed sunshade system, the use of high TRL deployment mechanisms, such as AstroMasts or coilable boom assemblies, and the overall lower risk of deployment due to fewer mechanisms. New challenges include the larger sunshade size, venting of the stowed sunshade during ascent, and the immediate exposure of the payload to the environment once the fairing is jettisoned.

5. FUTURE WORK

Looking ahead, the LUVOIR team continues to develop both of the LUVOIR architectures for consideration by the Decadal Survey committee. Additional detail of the optical, mechanical, structural, and thermal models continues to be developed as system performance and science yield is quantified.

Additionally, the team continues to draft a technology development plan, identifying key enabling technologies and desirable enhancing technologies. An early assessment of the technology readiness level (TRL) has been completed (see Chapter 11 of [2]), and a roadmap for developing the most promising technologies to TRL 6 will be submitted with the LUVOIR final report.

In the summer of 2019, all four mission concepts will submit their final reports to the National Academy of Science Decadal Survey Committee. A final prioritization of missions is expected from the National Academies by the end of 2020.

ACKNOWLEDGEMENTS

The LUVOIR Study is funded by NASA HQ and Goddard Space Flight Center, volunteered time of the STDT members, as well as in-kind contributions through a Cooperative Agreement Notice. The Pollux instrument design is an international contribution by CNES.

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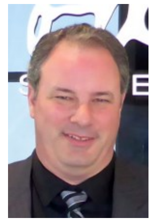
BIOGRAPHY



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