The Large UV/Optical/Infrared Surveyor Decadal Mission Concept Thermal System Architecture

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The Large Ultraviolet/Optical/Infrared (LUVOIR) Surveyor is one of four large strategic mission concept studies commissioned by NASA for the 2020 Decadal Survey in Astronomy and Astrophysics. Slated for launch to the second Lagrange point (L2) in the mid-to-late 2030s, LUVOIR seeks to directly image habitable exoplanets around sun-like stars, characterize their atmospheric and surface composition, and search for biosignatures, as well as study a large array of astrophysics goals including galaxy formation and evolution. Two observatory architectures are currently being considered which bound the trade-off between cost, risk, and scientific return: a 15-meter diameter segmented aperture primary mirror in a three-mirror anastigmat configuration, and an 8-meter diameter unobscured segmented aperture design. To achieve its science objectives, both architectures require milli-Kelvin level thermal stability over the optics, structural components, and interfaces to attain picometer wavefront RMS stability. A 270 Kelvin operational temperature was chosen to balance the ability to perform science in the near-infrared band and the desire to maintain the structure at a temperature with favorable material properties and lower contamination accumulation. This paper will focus on the system-level thermal designs of both LUVOIR observatory architectures. It will detail the various thermal control methods used in each of the major components – the optical telescope assembly, the spacecraft bus, the sunshade, and the suite of accompanying instruments – as well as provide a comprehensive overview of the analysis and justification for each design decision. It will additionally discuss any critical thermal challenges faced by the engineering team should either architecture be prioritized by the Astro2020 Decadal Survey process to proceed as the next large strategic mission for development.

Nomenclature

α = Absorptivity
AOS = Aft Optics System
BK = Black Kapton coating
BP = Backplane
BSF = Backplane Support Fixture
C&DH = Command and Data Handling System

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CMG = Control Moment Gyroscope, part of the Attitude Control System
Comm = Communications System
CTE = Coefficient of Thermal Expansion
ΔT = Change in temperature
ε, ε^* = Emissivity, effective blanket emissivity
ECLIPS = Extreme Coronagraph for Living Planetary Systems instrument
FSM = Fast Steering Mirror
GBK = Germanium Black Kapton
GSFC = NASA Goddard Space Flight Center
HDI = High Definition Imager instrument
IR = Infrared
LES = Low-Emissivity Shield
LUMOS = LUVOIR Ultraviolet Multi-object Spectrograph instrument
LUVOIR = The Large Ultraviolet/Optical/Infrared Surveyor
K = Kelvin
m = Meter
MEB = Main Electronics Box
MLI = Multi-Layer Insulation
NASA = National Aeronautics and Space Administration
OTA = Optical Telescope Assembly
PAS = Payload Articulation System
PDU = Power Distribution Unit
PLES = Primary Mirror Segment Assembly Low-Emissivity Shield
PM = Primary Mirror(s)
PMSA = Primary Mirror Segment Assembly
PMB = Primary Mirror Backplane
Prop = Propulsion System
PSE = Power System Electronics
SC = Spacecraft
SM = Secondary Mirror
SMA = Secondary Mirror Assembly
SMSS = Secondary Mirror Support Structure
TM = Tertiary Mirror
TMA = Tertiary Mirror Assembly
ULE = Ultra Low Expansion glass
UV = Ultraviolet
VDA = Vapor-Deposited Aluminum coating
W = Watt(s)

I. Introduction

THE Large Ultraviolet/Optical/Infrared Surveyor (LUVOIR) is a multi-wavelength general-purpose space observatory commissioned by NASA as one of four large strategic mission concept studies for the 2020 Decadal Survey in Astronomy and Astrophysics. The size and scope of LUVOIR enables a broad range of astrophysics to be performed, including characterization of the reionization epoch, galaxy and planet evolution, and star and planet formation. Another of LUVOIR's key science goals is to directly image a wide range of exoplanets to understand their atmospheric and surface composition. By assessing their habitability and searching for the presence of any biosignatures, it seeks to answer the question: "are we alone?", and if life is present elsewhere, "how common is it?" This set of demanding science objectives entails rigorous engineering requirements, such as a large aperture, a broad spectrum of wavelength sensitivities from near-infrared (IR) to ultraviolet (UV), and picometer-level wavefront stability enabled through both extreme thermal stability and active mechanical control[1,2].

Two architectures were chosen by the LUVOIR team to study in detail, which bound the range of primary mirror diameter, launch mass, and volume, as well as scientific return, cost, and risk. LUVOIR-A is a 15 meter diameter segmented aperture primary mirror in an on-axis design, while LUVOIR-B has an 8 m diameter unobscured segmented aperture primary mirror with an off-axis design. Both LUVOIR architectures are also actively heated to 270 K to maintain the composite structure and Ultra Low Expansion glass (ULE) mirrors at a temperature conducive to thermal stability, taking advantage of material properties that result in a near-zero coefficient of thermal expansion (CTE). This operating temperature was also chosen both to balance the ability to perform science in the near-IR, in which colder temperatures are desirable, and the need to keep the system above 260 K to take advantage of favorable material properties for stability. The telescope optical elements are also held to a thermal stability requirement of ±0.001 K to achieve the ultra-stable wavefronts necessary to enable high-contrast exoplanet science. LUVOIR-A and LUVOIR-B each carry a suite of science instruments. Three are shared by the two architectures: the Extreme Coronagraph for Living Planetary Systems (ECLIPS) is a near-UV / optical / near-infrared coronagraph; the LUVOIR UV Multi-object Spectrograph (LUMOS) provides multi-object imaging spectroscopy in the 100-1000 nanometer range; and the High Definition Imager (HDI) is a wide field-of-view near-UV / optical / near-IR camera that can also perform astrometry. A fourth instrument, Pollux, is a far-to-near UV spectro-polarimeter currently being studied by a consortium of European partners, led by the Centre National d'Études Spatiales (CNES)[3]. However, due to mass and volume limitations on LUVOIR-B, Pollux is only considered for inclusion on LUVOIR-A. A more comprehensive look at the trade studies which gave rise to these two architecture designs can be found in the LUVOIR Interim Report[4].

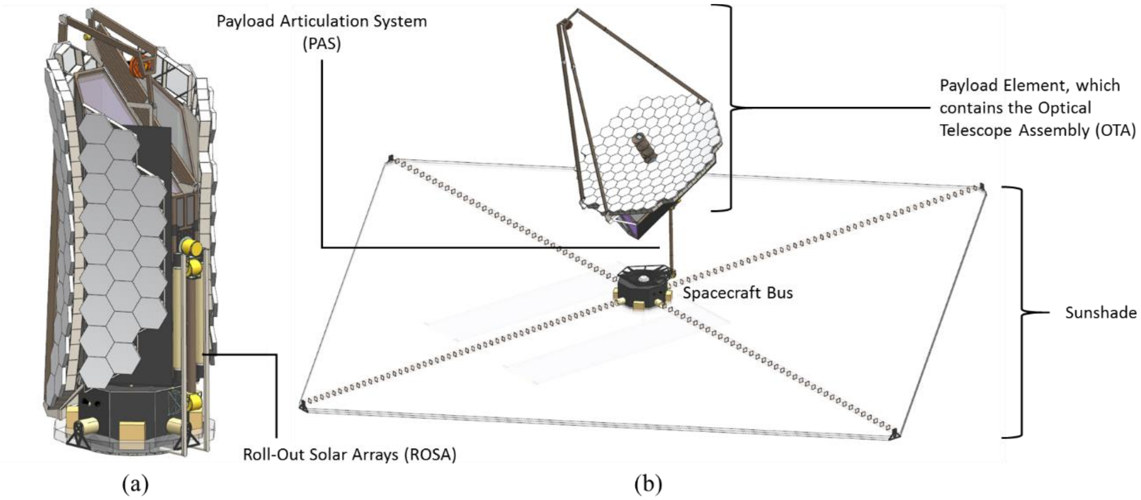

Figure 1. The 15 m Large Ultraviolet/Optical/Infrared Surveyor (LUVOIR-A) in (a) Stowed and (b) Deployed Configuration

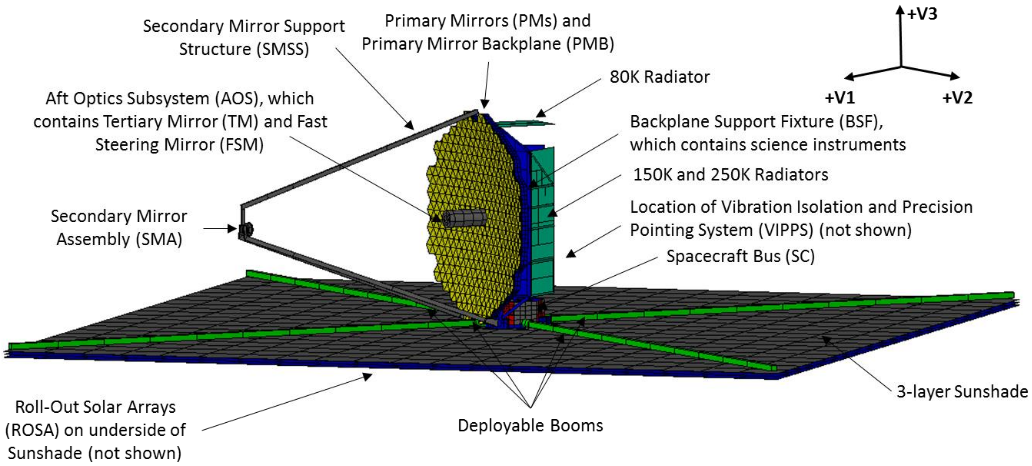

Figure 2. The LUVOIR-A Thermal Model, with major components denoted

LUVOIR-A is shown in its stowed configuration in Figure 1(a). The stowed LUVOIR-A is designed to be able to fit into the volumetric constraints of NASA's planned Space Launch System Block 2 vehicle at 8.4 m x 27.4 m, while LUVOIR-B has a volumetric requirement of a "conventional" heavy-launch vehicle fairing, such as a United Launch Alliance Delta IV-Heavy vehicle[5] at 5 m x 19.8 m. After launch, LUVOIR is placed into a transit orbit to the Sun-Earth Lagrange Point 2 (SEL2) and deploys en-route to the configuration in Figure 1(b).

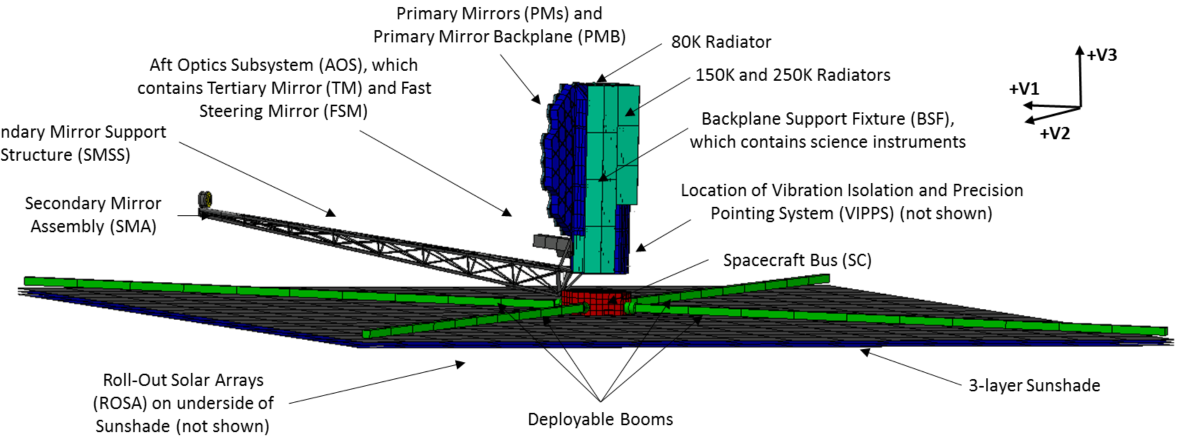

Figure 3. The LUVOIR-B Thermal Model, with major components denoted

A description of the major components and their locations for LUVOIR-A is shown in Figure 2. Note the V-axis system on the upper right-hand corner. Upon deployment, the Roll-Out Solar Arrays (ROSA) unfurl on the –V3 side of the sunshade, while a series of deployable booms extend the three sunshade layers in the V1 and V2 directions from the spacecraft bus to 80 m point-to-point in LUVOIR-A and 64 m point-to-point in LUVOIR-B. The Backplane Support Fixture (BSF), which contains the science instruments, releases from its launch locks to mechanically and thermally decouple from the spacecraft bus. The secondary mirror support structure (SMSS) unfolds from behind the primary mirrors, placing the Secondary Mirror Assembly (SMA) at the focus of the primary mirror array. Afterwards, the segmented Primary Mirrors (PMs), mounted onto a composite Backplane (BP) structure and attached to the Backplane Support Fixture (BSF) in launch, now deploy to form a uniform optical surface viewing the +V1 direction. Finally, the Aft Optics System (AOS), which contains the Tertiary Mirror (TM) and Fast Steering Mirror (FSM), telescopically extends to its deployed position ahead of the primary mirror plane. A similar suite of components are echoed in the LUVOIR-B architecture, as shown in Figure 3. LUVOIR-B undergoes a comparable deployment sequence as LUVOIR-A except for one crucial difference: to prevent obscuration of the primary mirror, the SMSS consists of a single truss structure protruding from the BSF, –V3 to the primary mirror array. When deploying, three stacked flat panels unfold and latch to form a beam with a triangular cross-section. The AOS then telescopically extends from its position below the PMs.

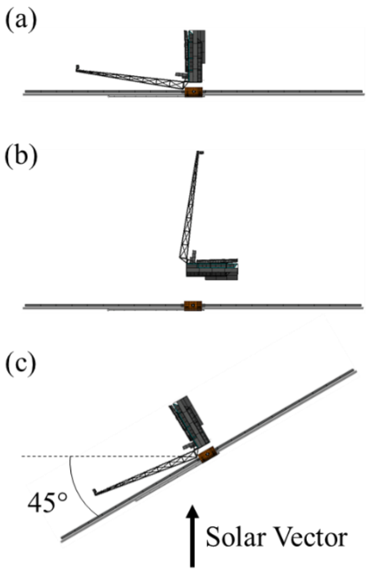

Figure 4. Worst-case thermal environments for LUVOIR: (a) sunshade pitch 0°, OTA pitch 90°; (b) sunshade pitch 0°, OTA pitch 0°; (c) sunshade pitch 45°, OTA pitch 90°

For both architectures, a series of radiators held at 150 K and 250 K are fixed on the V2 sides of the BSF to dissipate heat from instrument components and electronics boxes held at 170 K and 270 K, respectively. A select few near-infrared (IR) detectors held at 100 K on the ECLIPS and HDI instruments transport their heat to the 80 K radiator on the +V3 side of the BSF. While the +V3 side provides the most unobstructed views of deep space and the most desirable sink temperatures, the availability of real estate on this side is not sufficient to accommodate all of the required radiator area for LUVOIR's heat dissipation. Therefore, only the 80 K radiator occupies the +V3 side since it has the most stringent passive cooling requirements, while the 150 K and 250 K radiators are relegated to the V2 sides and are oversized to account for backloading from the payload and sunshade. The Payload Articulation System (PAS), as seen in Figure 1(b), allows the Payload Element, which contains the Optical Telescope Assembly (OTA), to both pitch and roll independent of the orientation of the spacecraft and sunshade to acquire its scientific targets. From trade studies in its SEL2 environment, it was determined that the orientations in Figure 4 bound the range of thermal environments encountered by the observatory. In the LUVOIR convention, the sunshade and spacecraft orientation is described separately from the Payload orientation. The sunshade orientation is taken with respect to the solar vector, where a positive pitch angle describes the sunshade's cant towards the solar vector. The OTA pitch angle denotes the Payload's orientation with respect to the sunshade, not the environment. An OTA pitch of 90° implies that the optical axis of the telescope is parallel to the sunshade, while an OTA pitch of 0° places the optical axis perpendicular to the sunshade. The sunshade pitch can only be positive if the OTA pitch is at 90°. Thus, for Figure 4(a), a sunshade pitch of 0° and OTA pitch of 90° allows for significant backloading onto the –V3 sides of the Payload components, reducing the overall Payload heater power, and provides the coldest sinks for the +V3 radiator which views deep space. For Figure 4(b), this orientation allows for sunshade backloading on the –V1 sides of the BP and BSF, but represents a worst-case for 80 K radiator area since it now has a view to the warmer sunshade. Figure 4(c) does not actually result in solar impingement on the OTA, and therefore does not change the heat flux on the optical telescope. However, for the spacecraft bus, this configuration causes the +V1 side to experience much greater environmental loading versus the –V1 side, and therefore impacts the heater power required to hold the bus at 270 K.

II. Thermal Architecture

Despite active heating of many of its components to 270 K, LUVOIR relies on a heavily passive thermal design to transport and reject its heat to space. The intent of the thermal architecture is to efficiently transport and reject all internal heat dissipations to space via heat pipes and radiators, while insulating the actively heated components as much as possible to conserve heater power. The thermal design is also intended to be modular, partitioning each separate assembly into its own thermal zone and reducing the amount of cross-talk between the components.

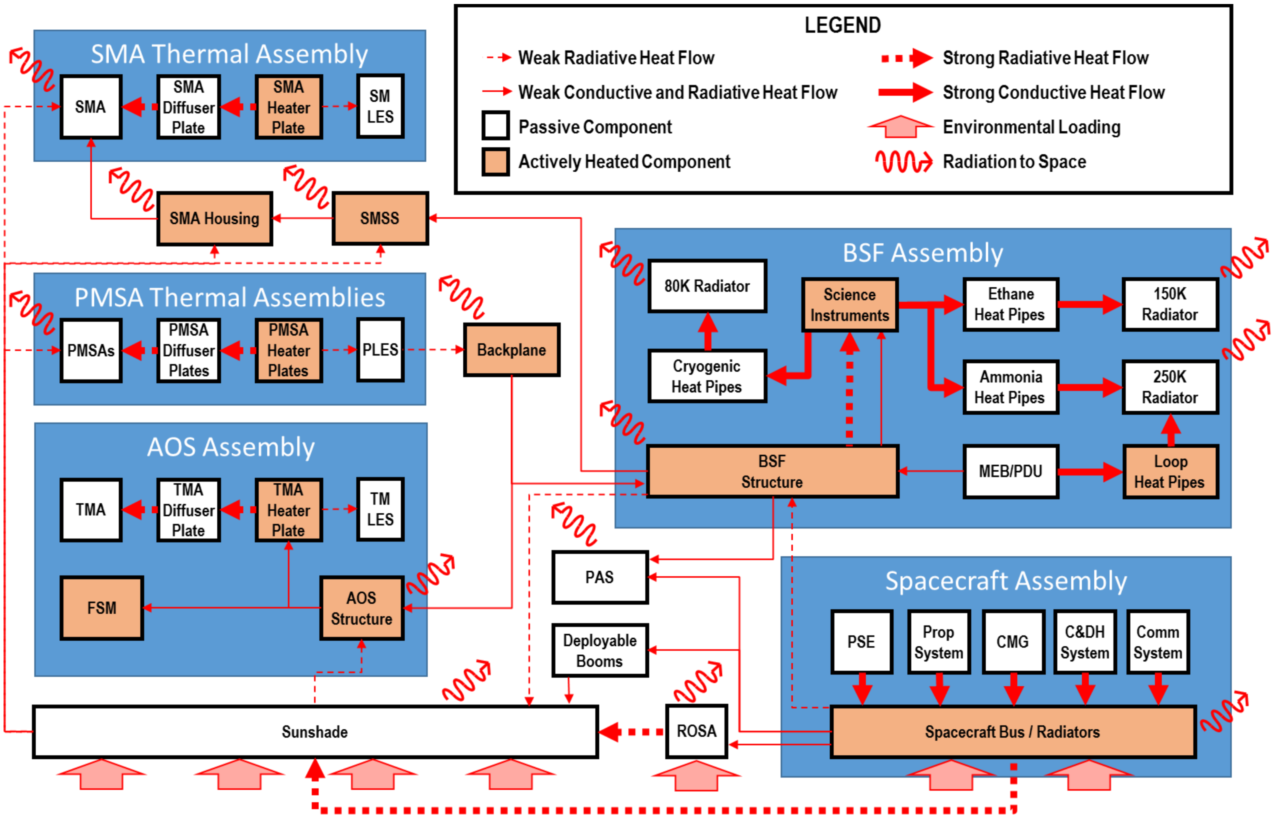

Figure 5. Major Heat Flows in the LUVOIR System-Level Architecture

Figure 5 shows the major system-level heat flows for both LUVOIR architectures. Components are denoted with either a shaded box, implying that it is actively heated, or a white box, indicating passive thermal control. The thin dashed lines denote weak radiative heat flows between components, while thin solid lines denote weak conductive and radiative heat flow. Conversely, thick dashed and solid lines respectively imply strong radiation and conduction. There are also symbols indicating that a component is subject to environmental loading or radiates its heat to space. Beginning at the bottom of the figure, the only components to receive direct solar loading are the sunshade, the ROSA, and the surfaces of the spacecraft bus which protrude past the –V3 sunshade layer. From a detailed trade study, the sunshade was determined to provide the coldest sink environment to the BSF radiators with a silicon-doped vapor-deposited aluminum (VDA) coating on Kapton for the sun-facing side of the –V3 layer, and VDA for all of the inner-facing surfaces for the –V3, mid, and +V3 sunshade layers, very similar to the design for the James Webb Space Telescope sunshield. The Payload-facing surface on the +V3 sunshade layer is coated with Black Kapton (BK) to provide a non-specular surface for the optical telescope and reduce the amount of stray light entering the optical path. This +V3 surface achieves an average temperature of 95 K on LUVOIR-A and 75 K on LUVOIR-B in the 0° sunshade pitch orientation, providing a cold sink for the radiators at a cost of higher heater power. The ROSA, due to its high resultant temperatures from direct solar impingement, is isolated conductively through M55J composite booms to the spacecraft bus. The backside of the solar array panels are painted with Z93 white paint to allow them to radiate the heat absorbed from the sun-facing side. While this re-radiated heat directly impinges on the –V3 sunshade layer, locally increasing temperature gradients adjacent to the ROSA, it does not have a significant impact on the Payload past the +V3 sunshade layer.

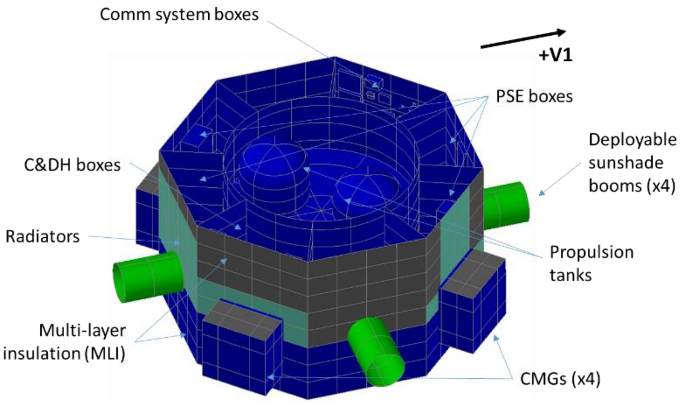

Figure 6. Major components on the LUVOIR-A Spacecraft Bus

The spacecraft bus is an octagonal structure assembled with composite honeycomb panels, as shown in Figure 6. The Power System Electronics (PSE) boxes, the four Control Moment Gyroscopes (CMGs) of the attitude control system, and the boxes for the Command and Data Handling (C&DH) and Communication subsystems all directly mount to the internal-faces of these bus panels with silicone thermal interface material to facilitate heat conduction from their baseplates. The external faces of these panels are covered with Z93 white paint where heat rejection is desired, while Germanium Black Kapton (GBK) outer layer Multi-layer Insulation (MLI) blankets with $\varepsilon^* = 0.03$ cover all non-radiator surfaces. These external-facing panels are also actively heated to maintain a 270 ± 3 K requirement. Additionally, ammonia heat pipes are embedded in those panels which have high heat-dissipating components mounted on the internal face, and therefore require both through-thickness conduction to the external-facing radiator as well as lateral spreading to reduce the bus panel in-plane temperature gradients. The propulsion tanks are embedded at the center of the spacecraft bus and both radiate and conduct their heat dissipations out through the bus structure to the external panels. For all of the internal-facing surfaces inside the bus enclosure, the panels are left as bare composite and the boxes are covered with high-emissivity BK to isothermalize the bus via radiative heat exchange.

Extending in the +V3 direction from the bus, the PAS structure allows for weak conduction to the Payload Element and its associated components. The BSF structure represents a critical thermal and mechanical hub for the Payload, supporting the backplane, the AOS, and the complement of science instruments. As previously mentioned, the Payload radiators are mounted to the V2 and +V3 sides of the BSF. The BSF structure itself consists of two major elements: a truss structure composed of hollow rectangular-cross-section M55J composite beams covered on all external sides with VDA MLI, and a series of composite shear panels framed by the beams on the V1 and V2 sides, covered with VDA MLI on the space-facing sides but BK on the internal-facing surfaces. Both elements are actively heated to 270 K: the VDA MLI covering the beams is intended to minimize the amount of heater power required; however, for the panels, while the external-facing VDA MLI prevents heat from being lost to space or impinging on the radiators, the internal BK coating allows heat from the panels to provide a warm source for the instruments, reducing the amount of heater power required to maintain each of their optical benches at 270 K. The V3 sides of the BSF are capped with

VDA MLI to prevent heat loss to space, and to reduce the amount of heat absorbed on the –V3 side from its view to spacecraft bus in the OTA pitch 90° position. Figure 7 shows BSF structure for both LUVOIR architectures with and without the radiators; the truss members and radiators are shaded in blue, the composite shear panels are in red.

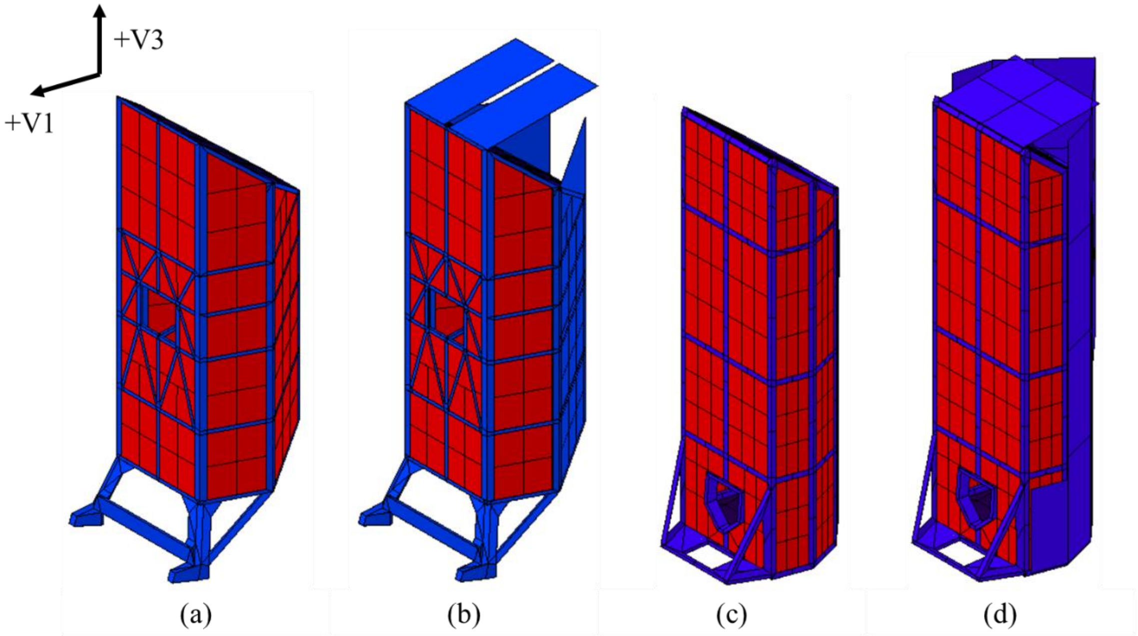

Figure 7. BSF Structure for (a) LUVOIR-A without radiators; (b) LUVOIR-A with radiators; (c) LUVOIR-B without radiators; (d) LUVOIR-B with radiators

For the instruments, each instrument is positioned inside the BSF cavity with their 270 K optical assemblies wrapped with BK SLI or MLI to allow for a small amount of radiative heat flow in from the BSF panels while dampening any transient temperature changes or spatial gradients. The intent of this design is to isolate the instruments from BSF heater performance while minimizing the amount of heater power required to drive the instrument optical benches to their operating temperatures. The 270 K components on the optical benches dissipate their heat via Ammonia heat pipes to their dedicated 250 K radiators on the V2 sides of the BSF. The only exception is the high-power Payload Main Electronics Box (MEB) and Power Distribution Unit (PDU), which require an active loop heat pipe to transfer their high heat loads. For components at 170 K, these are heat-strapped to Ethane heat pipes to transport their heat to the colder 150 K radiators. The few detectors at 100 K on the ECLIPS and HDI instruments deliver their waste heat through specialized, nitrogen-filled cryogenic heat pipes to the +V3 80 K radiators. A more extensive discussion of instrument thermal design can be found in Yang et al[6]. A 20 K ΔT is assumed for parasitics and conductive losses from the instruments to the radiators. The colder 170 K and 100 K components are also wrapped with VDA MLI to avoid absorbing as much of the BSF panel heat as possible. The BSF radiators conductively isolated from the body of the BSF structure through standoffs, and have VDA MLI on their BSF-facing side and high-emissivity Ball Infrared Black (BIRB) paint on their space-facing surfaces.

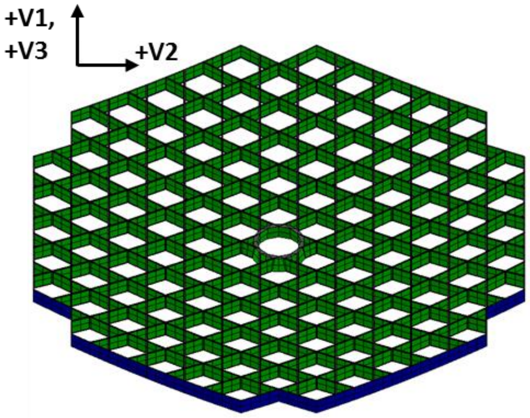

Figure 8. LUVOIR-A BP composite structure: Green is bare M55J, Blue is VDA MLI

For both LUVOIR architectures, the optical telescope assemblies are mounted to the +V1 side of the BSF. The backplane structure is composed of a lattice of M55J composite I-beams in the V2/V3 plane, as shown in Figure 8. An array of

120 PMSAs on LUVOIR-A and 55 PMSAs on LUVOIR-B are mounted +V1 of the backplane structure, while the cavities on the –V1 side are closed out with VDA MLI. A trade study was performed to ascertain the most efficient way to heat this structure to 270 K. It was determined that if all of the internal I-beams were left as bare M55J, while the external space-facing edges were covered with VDA MLI, it would both minimize mass and heater power. For a preliminary systems-level understanding of the amount of heater power required to maintain this component at its operational temperature, it was sufficient to leave all nodes bounded at 270 K in the thermal model and avoid simulating individual heaters. As the backplane is a large determinant to the overall PMSA stability, however, future trade studies will need to focus on the methods for achieving ultra-stable control despite the cross-talk between heaters on each I-beam and the uneven distribution of harness heat through the structure.

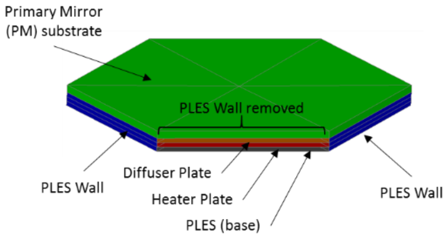

Figure 9. Sample PMSA Thermal Assembly

Returning to Figure 5, a significant portion of this heat flow chart has been devoted to describing the thermal assemblies for the PMSA, the SMA, and the TM. For these mirror architectures, preliminary trade studies showed that direct heating of the mirror substrates is not feasible since it would unacceptably disturb both the thermal and optical stabilities of the mirrors themselves, beyond their requirements. Therefore, a thermal assembly is devised to allow for active heating of the mirror without direct contact between the heater and the mirrors. For each of these mirrors, immediately behind the mirror substrates on the non-reflective side, there is a diffuser plate, a heater plate, and a low-emissivity shield (LES) with the same surface area as the mirror face. An example is shown for one PM segment in Figure 9. The heater plate is actively controlled to radiatively drive the temperature on the mirror substrate to 270 K, while the diffuser plate is a passive 2-mm-thick Aluminum spreader with a high-emissivity coating on both sides to smooth the spatial and temporal gradients from the heater plate. The low-emissivity shield, referred to as the PLES for the primary mirrors and the SM LES and TM LES for the secondary and tertiary mirrors, is a pan-like rigid thin aluminum structure with walls extending towards the mirror substrate at its edges. To reduce radiative losses from the thermal assemblies, the LES is covered with VDA SLI on both sides and its walls extend as close as possible to the mirror substrate without interfering with the mirror motion. Note that while there is a singular mirror assembly for the SM and TM, this thermal assembly is repeated for every primary mirror segment, with a mass per thermal assembly of approximately 11 kg for LUVOIR-A and 7 kg for LUVOIR-B. In these thermal assemblies, the heater plate is also the only actively-controlled thermal component. The SMA, specifically, has active heating for both its heater plate and the cylindrical housing for its thermal control and mechanical drive assemblies. The SMSS is also actively controlled to 270 K to limit alignment distortions due to CTE, and both the SMA and SMSS are covered in BK outer layer MLI both to reduce the amount of heater power lost to the environment, as well as to reduce the amount of stray light into the optical path. In contrast to the other mirrors, the FSM has a heater directly mounted on the underside of the mirror substrate due to its large range of motion and small size, which maintains a relatively isothermal mirror surface despite not using a heater plate assembly.

III. Preliminary Thermal Results

The LUVOIR-A and LUVOIR-B thermal models were generated with Thermal Desktop and SINDA/FLUINT analysis software. The LUVOIR-A model contains approximately 21000 nodes while the LUVOIR-B model contains 10400 nodes. All of the presented results are analyzed in steady-state, since transient thermal effects during the mission operational phase are expected to be minimal given the stable thermal environment of SEL2. Also, given the high-level conceptual nature of the current study, these models were developed primarily to generate preliminary estimates for radiator area and heater power rather than to provide realistic responses over time to environmental perturbations or configuration changes.

To conservatively size the radiators at this conceptual phase, the 170 K component parasitics have a margin of 50% added, while for the 100 K component parasitics, a margin of 100% is added[7]. For the heater powers, a 40% uncertainty margin is included in the predictions[8]. Table 1 shows the model-estimated heater powers for LUVOIR-A divided by subsystem. The corresponding numbers for LUVOIR-B are in Table 2. As seen from the tables, the PM segment heater plates by far consume the most heater power out of any OTA component. This is due to the sheer number of mirror segments per architecture, as well as the inefficiency from using indirect radiative heating to drive the primary mirror substrates to 270 K. For many segments, the PM heater plates need to be set at 280 K or higher to achieve the target PM substrate temperature, given both conductive and radiative losses to adjacent components and the environment. Though the SMSS, SMA, and the AOS structure forward of the PMs are directly heated and covered with MLI, they also have significantly high heater powers due to their high-emissivity BK outer layer to reduce stray light. This is more immediately apparent with the LUVOIR-B architecture, since the deployable truss structure of the SMSS has a large surface area with a radiative view to deep space. Conversely, the Backplane and BSF structures, both being very well insulated from their environment and having a low-emissivity VDA outer layer facing space, consume significantly lower heater power despite their large surface areas.

LUVOIR-A	Required Heater Power (W)		
Orientation	Sunshade 0°, OTA 90°	Sunshade 0°, OTA 0°	Sunshade 45°, OTA 90°
Backplane	488	498	489
PM Segment Heater Plates	2798	2914	2792
BSF	477	497	480
SMSS and SMA	346	348	346
AOS Structure, TM, and FSM	133	144	135
Spacecraft Bus	1413	2126	1602
TOTAL CBE	5655	6527	5844
TOTAL with 40% Heater Margin	9425	10878	9740

Table 1. Preliminary Estimate of LUVOIR-A Heater Powers

LUVOIR-B	Required Heater Power (W)		
Orientation	Sunshade 0°, OTA 90°	Sunshade 0°, OTA 0°	Sunshade 45°, OTA 90°
Backplane	164	163	164
PM Segment Heater Plates	890	936	891
BSF	455	451	455
SMSS and SMA	531	534	531
AOS Structure, TM, and FSM	104	107	104
Spacecraft Bus	1114	2475	1064
TOTAL CBE	3258	4666	3209
TOTAL with 40% Heater Margin	5430	7777	5348

Table 2. Preliminary Estimate of LUVOIR-B Heater Powers

The Spacecraft Bus heater powers reflect the amount of heat required to actively drive the bus with no heat dissipations from the boxes to its required setpoints. With average operational heat dissipations from all of the subsystem boxes within the SC, heater power reduces by 30-45%. As seen in the tables, the SC heater power sees much greater impact from a change in sunshade and OTA pitch than the Payload itself. With an OTA pitch of 0°, the SC radiators no longer receive much backloading from the Payload, and therefore experience much colder sinks, requiring more heater power to maintain 270 K setpoints. However, with sunshade pitch greater than 0°, the –V3 side of the sunshade experiences changes in environmental loading, additionally impacting the amount of heater power necessary. The SC heater power required for both LUVOIR architectures is also comparable since, despite the difference in bus sizes, their sink temperatures and required radiator areas are similar. Due to high power demand for both heaters and onboard electronics, the required solar array areas are 290 m^2 for LUVOIR-A and 222 m^2 for LUVOIR-B.

Calculated radiator areas based on the heat dissipations and parasitics within each LUVOIR architecture are tabulated for each OTA temperature zone and the spacecraft bus in Table 3. For the OTA, LUVOIR-A has enough real estate on the BSF V2 sides for the 250 K and 150 K radiators, and also enough on the +V3 side to accommodate the required area for the 80 K radiator. On LUVOIR-B, while area on the +V3 side is sufficient for the 80 K radiator, the addition of a fixed V-shaped extension on the aft (-V1) side of the BSF is necessary to provide extra radiator space for the 150 K and 250 K zones. Fortunately, neither architecture require the use of deployables for extra area, greatly simplifying their design. Each radiator panel is embedded with a series of spreader heat pipes 0.1 m apart down its length to facilitate heat transfer, with the 80 K radiators using nitrogen as a working fluid, and the 150 K and 250 K using ethane and ammonia, respectively. Radiator panels exist on each side of the Spacecraft Bus which contain an internally-mounted powered component, with MLI covering any areas where radiator is not desired. All panels with heat-dissipating components also contain embedded ammonia spreader heat pipes to even gradients and prevent box baseplates from overheating.

	LUVOIR-A		LUVOIR-B	
	Required Area (m^2)	Max Sink Temp (K)	Required Area (m^2)	Max Sink Temp (K)
250 K OTA Radiators	66.1	105	34.7	95
150 K OTA Radiators	6.9	105	5.7	95
80 K OTA Radiators	4.4	70	2.4	58
Spacecraft Bus Radiators	9.7	232	11.5	192

Table 3. Preliminary Estimate of LUVOIR Radiator Areas

IV. Conclusion and Recommendations

A design for active and passive control of the two LUVOIR architectures to their thermal requirements has been presented in this current work. LUVOIR is dependent on active heater control to reach its target temperatures on the Payload and Spacecraft Bus, but mostly reliant on passive control to reject waste heat from its separate thermal zones to space. MLI is used extensively to reduce the amount of heater power required and decrease the parasitics to the colder thermal zones. For the PMs, SM, and TM, heater panels are employed to radiatively heat these mirrors while minimizing the disturbance to their stabilities. Preliminary thermal model results show that large amounts of heater power are required for both the Payload and Spacecraft Bus to maintain their setpoints. However, for the Payload, changes in heater power are much more independent of sunshade orientation and environmental loading than for the SC. Also, while Payload power is significantly smaller for LUVOIR-B than LUVOIR-A, on the SC these power requirements are comparable between architectures. Regarding radiator areas, initial estimates show that both LUVOIR architectures have enough surface area to accommodate fixed radiators for each of the thermal zones, and the use of deployables is not necessary.

Further work on the LUVOIR architectures require a series of thermal challenges to be addressed through in-depth studies. The paramount thermal difficulty for the LUVOIR architecture is to achieve the thermal stability required to enable picometer-level wavefront stability. On the composite structures, the current model sets all actively-controlled surfaces as boundary nodes at their desired setpoints to estimate the amount of heater power required to hold each component. However, it does not speak to the heater placement or implementation, or calculate the spatial temperature gradients that might form due to such. A detailed study of heater placement and control is necessary to understand if and how active thermal control at these extremely high stability requirements may be achievable. Similarly, for heater plates controlling the PMs, the SM, and TM, bounding the heater panel nodes only estimates heater power, but does not reveal how active control to 0.001 K-level stability could be implemented, especially if a feedback loop is needed to allow for the heater panel to drive the mirrors to 270 K. For the PMs, this is particularly a concern, since any single segment's heater control might be influenced by excess heat dissipation from adjacent mirror segments, and this cross-talk between segments might be an unacceptable impact on thermal stability.

For the instruments, the greatest thermal challenges are to reduce the amount of parasitics to the colder components and transport heat efficiently to the dedicated radiators for each thermal zone. Since the BSF is actively heated to 270 K, and the instruments are embedded within the BSF cavity, their 170 K and 100 K components see a large amount of parasitic heat. To reject this heat, these components need an efficient conductive path directly to their radiators without driving a large ΔT for source to sink, and their dedicated radiators need to be large, highly emissive, and have good views to cold sinks. Given the immense dimensions on both LUVOIR-A and LUVOIR-B, and hence long distances between instruments and radiators, this presents a large challenge for efficient heat transport from source to radiator. Conversely, for the Spacecraft Bus, detailed study is required to increase efficiencies by balancing the amount of required radiator area versus insulation, trading heater power and heat rejection capacity. A particularly important study for this architecture will be the impact of MLI ε* assumptions, as small changes in the effectiveness of blanket insulation may result in large differences in heater power requirement, depending on how much heat is lost through the blanket layers. Greater optimization will achieve the best balance of low heater power requirement and cold-bias for heater control.

Verification of the thermal design is critical to the success of LUVOIR. Given the sheer size of both architectures and the stringent stability requirements necessary to meet science goals, a comprehensive test campaign is essential to prove the operability and robustness of the design. Early in hardware development, the control scheme for picometer-level wavefront stability must be demonstrated to be successful on a completed mirror assembly. As LUVOIR progresses to subsystem-level and system-level environmental testing, particularly given the size limitations of currently available test facilities, it may not be possible to test LUVOIR as a fully-integrated system. Therefore, capturing the correct environment and interfaces for any unit under test will be crucial to understand how well the LUVOIR thermal design will work at an observatory level. This includes tackling thermal challenges such as simulating the backloading from the sunshade and heat from missing adjacent components. Finally, LUVOIR's reliance on heat pipes both for transport of instrument heat dissipations and spreading of heat within radiators implies that orientation and levelness in ground testing is critical to the success of the thermal system. Thorough test planning will be required to ensure that any system-level testing is effective in addressing these concerns.

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