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Efficient Thermal Architecture for Large Space Telescopes

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ABSTRACT

Starting with a conceptual thermal model of LUVIOR-A, provided by NASA/Goddard Space Flight Center, alternate concepts of operations are explored. A candidate technology was identified to use solar power for rough first stage heating. That innovation reimagines what functions a solar array can have in a large telescope architecture. By combining electricity generation, stray-light control, and thermal control into one agile deployable structure, the heater power requirements could be improved by reducing the inefficiency of solar power conversion.

Keywords: Large, Space, Telescope, Architecture, Deployable, Adaptive, Heater

1. INTRODUCTION

The conceptual architectures for future large spaced-based telescopes combine proven approaches from previous missions as well as new or improved methods and technologies to achieve their ambitious science goals. One of the large mission concepts under evaluation by the Astro2020 Decadal Survey – the Large UV/Optical/Infrared Surveyor (LUVOIR) – consists of an open architecture and large sunshade which draws on the thermal architecture of the James Webb Space Telescope. The Webb sunshield is a precision deployed structure that prevents direct solar illumination and passively cools the telescope and instruments to cryogenic temperatures to achieve the low thermal background needed for infrared observations[1]. A similar approach was used for the LUVOIR sunshade, though key differences include a larger area to shield the payload at all pointing orientations as well as less stringent requirements on the deployment precision and fewer layers since LUVOIR does not need to be as cold[2]. In fact, the LUVOIR nominal operating temperature is 270 K, so a large amount of heater power is needed to bring the payload back up to temperature, which drives power requirements for the observatory and has multiple impacts on the spacecraft element design.

This paper examines the baseline 3000 m^2 deployable sunshade and explores alternative ideas for accomplishing the thermal conditions needed for this or similar missions. The ideas presented here aren't point designs. They are broad concepts for alternative architectures hoping to spur new innovations and the next generation of astrophysics scientific observations.

One of LUVOIR-A's key science goals is to directly image and characterize exo-planets, which requires a high level of thermal stability to achieve high contrast imaging with its coronagraph instrument. The NASA Goddard Space Flight Center (GSFC) provided the baseline Thermal Desktop[3] model shown in Figure 1. Figure 1 shows the deployed LUVOIR-A observatory with its 15m diameter primary mirror and 56m x 56m sunshade. It will be in a halo orbit at Lagrange point 2. Figure 2 shows the nominal viewing angles and revisit angles that extend toward the sun. Figure 3 defines the coordinate system relative to nominal bore sight, +Z. Rotations about X are referred to as pitch, rotations about Y are yaw and rotations about Z are roll.

In Section 2 the baseline LUVOIR-A design is discussed. The expected heater power as well as actual heater power for the normal field of view as well as the full field of view is explored with Veritrek generated plots. This is followed by a discussion of the asymmetry of the telescope in relation to the spacecraft and its effects on the heater power plots and how we can take advantage of this asymmetry with alternative technologies. Section 3 delves into one of these, the Sun Getter, in greater detail outlining its design and articulation patterns to reach the full field of view. This section also explores the way that spacecraft versus telescope articulations affect the total heater power and displays plots for both the normal field of view and the full field of view. Section 4 summarizes the findings of this paper.

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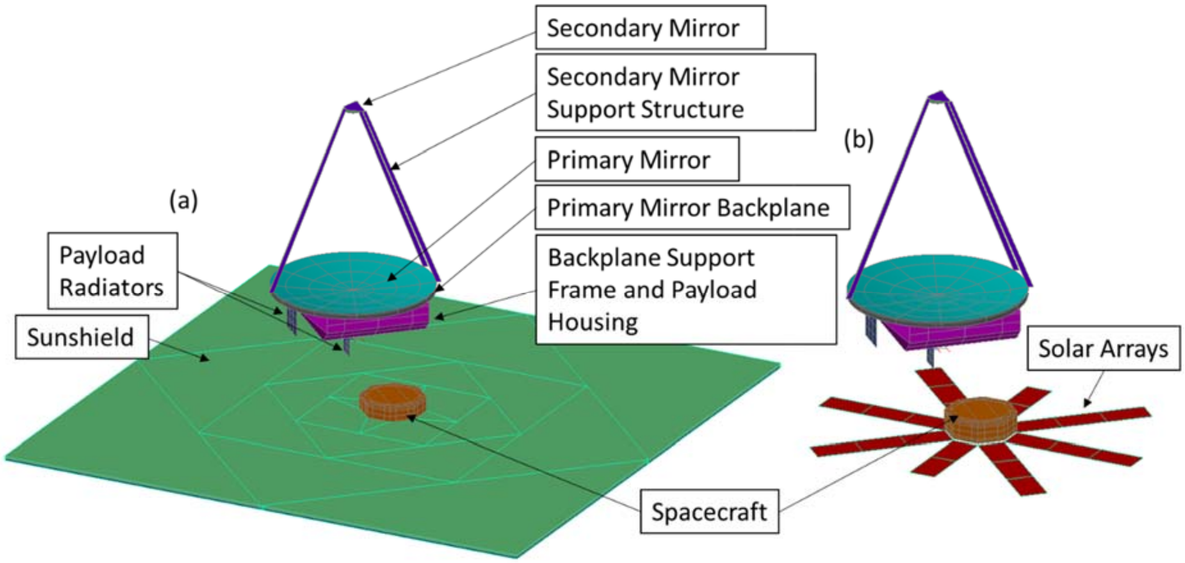

Figure 1. LUVOIR A Thermal Desktop Model (courtesy NASA/GSFC) (a) Shown with sunshade deployed (green) and (b) with sunshade removed to visualize solar arrays (red).

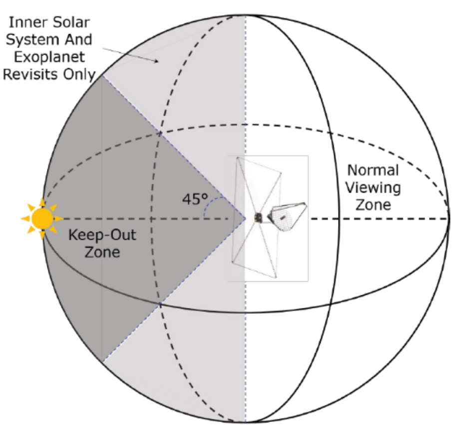

Figure 2. Desired Viewing Angles for the LUVOIR baseline mission concept. For observations in the nominal viewing zone (anti-sun hemisphere), the sunshade angle is fixed and the telescope points on a gimbal mount to the desired orientation. For observations into the sun hemisphere (light gray inner solar system area), the sunshade changes angle.

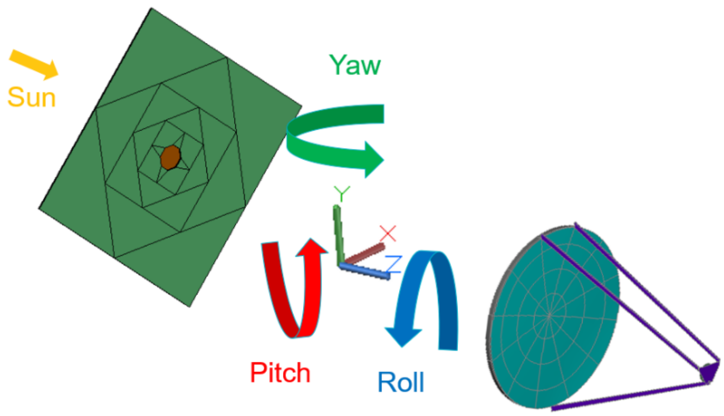

Figure 3. Axes of Rotation, exploded view

2. TELESCOPE HEATER POWER AND THE BASELINE LUVOIR-A CONCEPT

2.1 Telescope Heater Power with Telescope Articulation

The first study focused on LUVOIR baseline architecture and the resulting heat exchange between the fixed sunshade and the articulated telescope as a function of pointing. The baseline Payload Articulation System[2] consists of a gimbal arm and a Vibration Isolation and Precision Pointing System (VIPPS), though these structural elements are not included in the thermal model. Only major components that will be primary drivers of heater power are included in the model. Heater power to maintain the spacecraft at temperature is excluded in this section, focusing solely on heater power for the telescope and instruments. This section looks at normal viewing zone shown in Figure 2.

Engineering intuition would state that by keeping the sunshade in a fixed position relative to the sun, the thermal load on the telescope would remain constant. As the gimbal arm rotates the payload in X, Y, and Z throughout the Field of View, Figure 2, the relative distance between the telescope and the sunshade vary. These changes in distance will also change the net radiation heat transfer between the telescope and the sunshade, quantified by gray body view factors. Engineering intuition would also guide us to expect that the heater power required to maintain the telescope at 270K throughout the field of view would have a cosine like shape due to symmetry, as in Figure 4.

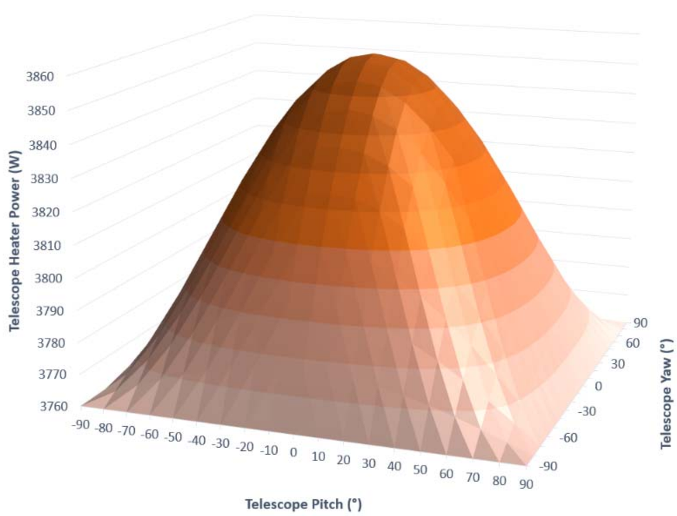

Figure 4. Expected heater power to maintain telescope at 270K as a function of pitch and yaw in Normal Viewing Zone using a flat plate analog and the cosine curve

Reduced Order Models (ROM) using Veritrek[4] were developed from training data generated using Thermal Desktop[3]. This ROM enabled rapid exploration of the operational envelope. All heater powers reported in the paper are raw estimates that do not contain modeling uncertainty factor or growth factors for apples-to-apples comparisons. The intent is to compare resource requirements for broad architecture trade comparisons, only. Detailed design work would necessitate both modeling uncertainty and growth factors for design maturation.

Baseline heater power for the telescope assembly is shown in Figure 5, which shows that the power required to heat the telescope structure to 270 K ranges from 3640 W to 3955 W. The differences between expected heater power, Figure 4, and the predicted heater power, Figure 5, are both striking and insightful. There is region of local minima located in one quadrant of the telescope pitch and yaw. Figure 6 shows heater predictions of just these local minima ranging from a telescope pitch of 0 to -90° and telescope yaw of 0 to +90°. The minima regions seen in figure 5 are highlighted with hash marked areas. The combination of telescope movements that result in these low power regions are shown together in Figure 6, bring the maximum heater power usage down to 3770 W. Using specific con-ops it's possible to confine the telescope movement to the Figure 6 region. This along with why the model is predicting minima regions will be explored in the upcoming sections.

Figure 6 is surprising and beneficial to the LUVOIR architecture. Heater power can be minimized simply by pointing the gimbal in one quadrant of the sky. The Normal Viewing Zone can be swept by rotating the spacecraft about Z, as required. This not only saves heater power; it simplifies the requirements of the gimbal arm from three axes of rotation to two. The notional gimbal arm design was envisioned[2] to be like the Space Station Remote Manipulator System (SSRMS). The SSRMS is capable of 7 degrees of freedom. However, with the discovery of a preferential quadrant within the Normal Viewing Zone, the required capabilities of such a system could be drastically reduced.

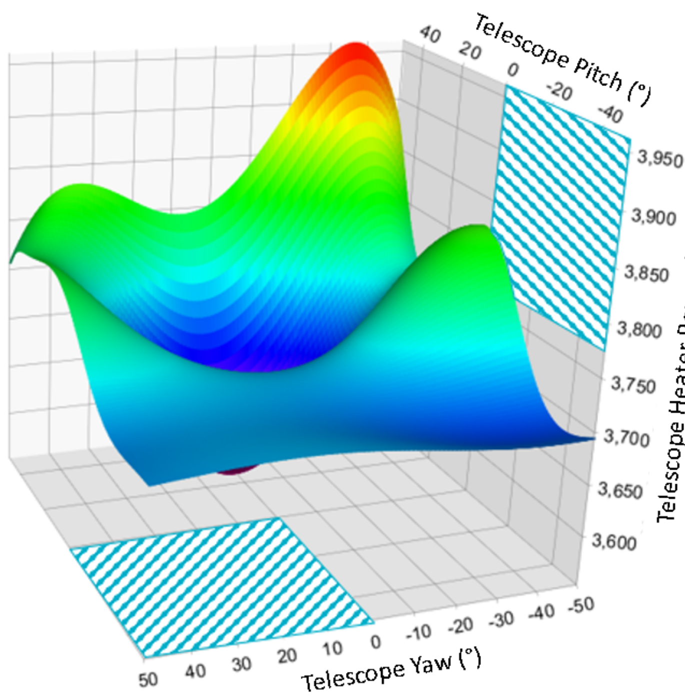

Figure 5. Predicted heater power required to maintain the telescope at 270K within a subsection of the Normal Viewing Zone, with low power regions highlighted with hashmarked areas

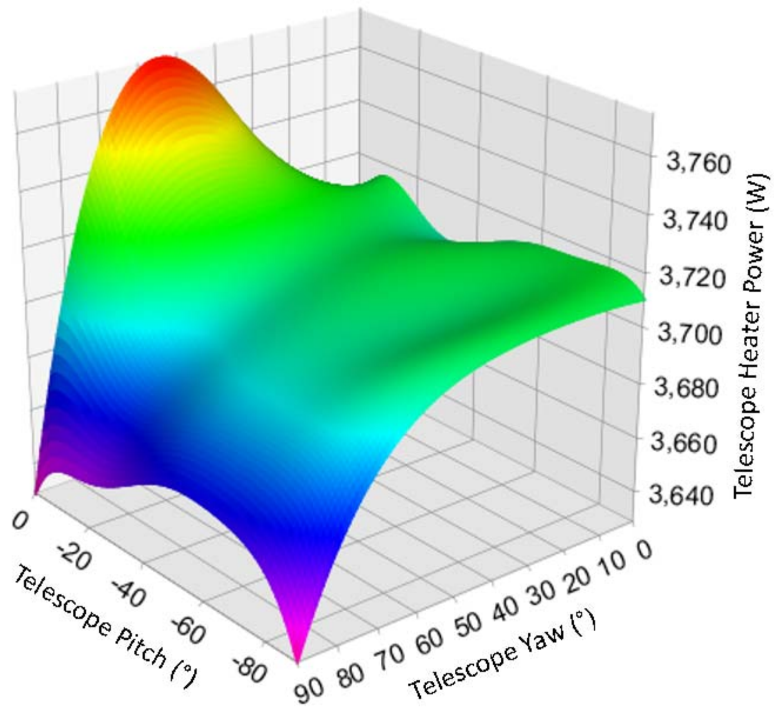

Figure 6. Heater power required to maintain the telescope at 270K from telescope pitch of 0 to -90° and telescope yaw of 0 to +90° inside the Normal Viewing Zone, combining local minima regions shows heater power reduction

2.2 Asymmetric View Factors

The large differences between the expected telescope heater power, Figure 4, and the predicted telescope heater power, Figures 6 and 7, prompted a closer look into the source of the asymmetric predictions. The telescope assembly is analytically disconnected from conducting heat between the telescope assembly and the spacecraft assembly. Any actual conducted power should be negligible by design. The only net heat transfer mechanism is long wave infrared radiation. The net radiation exchange is a function of temperature, geometry, distance, and emissivity.

Differences in emissivity can be immediately ruled out as the cause. Emissivity is known to change with time due to contamination, micrometeorite damage and age. However, the emissivities were held constant in this analytical study. The temperatures were also roughly constant over the telescope. The model's heater controllers adjusted the amount of heat to keep the telescope at 270K. Minor differences in temperature contours were noted and not suspected to be the source of the differences between Figure 4 and Figures 5 and 6. However, as LUVOIR has demanding temperature stability requirements how con-ops and shade structure effects the ability to hold stability through movements needs exploration.

The remaining two variables are geometry and distance. The geometry, the actual structure telescope and shade, is not changing during the articulations, but the projected area does change with angle. The change in projected area changes the view factor to the sunshield and is the primary cause of fluctuations in heater power. The same is true with distance. The distance between telescope assembly and the spacecraft assembly changes with angle. The projected area changes are expected. And as previously noted in Figure 4, expectations were a cosine plot. Examining the point of origin for both pitch and yaw rotations, Figure 7, shows a 4 m offset in the -Y direction, the shade is 56 m x 56 m, so the telescope is 1/7 the -Y distance. The telescope assembly in not centered on the spacecraft center. This explains part of the asymmetric predictions shown in Figures 5 and 6.

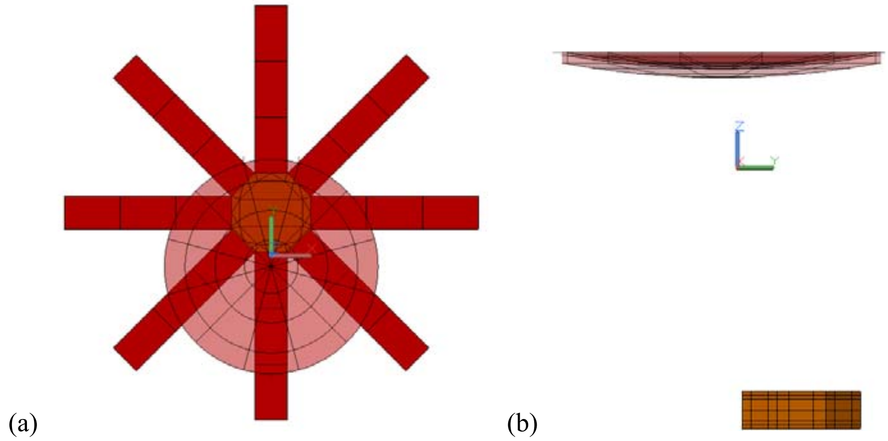

Figure 7. Telescope's axis of rotation is offset in Y, creating asymmetric views between the telescope, the spacecraft and the deployed sunshield (a) Top view from primary mirror down to spacecraft looking along -Z (b) Side view looking along -X. Sunshield, payload and secondary mirror structure removed for clarity. Model courtesy of NASA/GSFC.

Figure 8 shows three telescope rotations in X (pitch). Note the asymmetric design of the aft optics assembly, most notably the deployed radiators shown in Figure 8(b). Pitch in the positive direction, shown in Figure 8(a) with a rotation of +70°, moves the payload radiators in an undesirable location closer to the spacecraft and sunshield. Pitch in the negative direction, Figure 8(c) with a rotation of -70°, moves the radiators further away from the sunshield and the telescope assembly closer to the spacecraft. This is a very interesting observation and it presents an opportunity.

Not only can designers of these systems simplify gimbal arm requirements from many degrees of freedom to only two degrees, they can build in other features that take advantage of this favored quadrant, like the payload radiators. The effectiveness of the instrument radiators would be increased by the constraint added to have the telescope never pitch in the positive direction. By placing the radiators on the -Y side, they will always be cold biased and facing deep space. Likewise, components that operate near ambient temperatures would benefit by placement on the +Y side where they receive larger view factors to the warm spacecraft assembly. The asymmetry in the quadrant created by telescope pitch of 0 to -90° and telescope yaw of 0 to +90° opens up a lot of possibilities for telescope and payload designs to optimize the thermal efficiency of the architecture, though these must be balanced with spacecraft attitude control considerations.

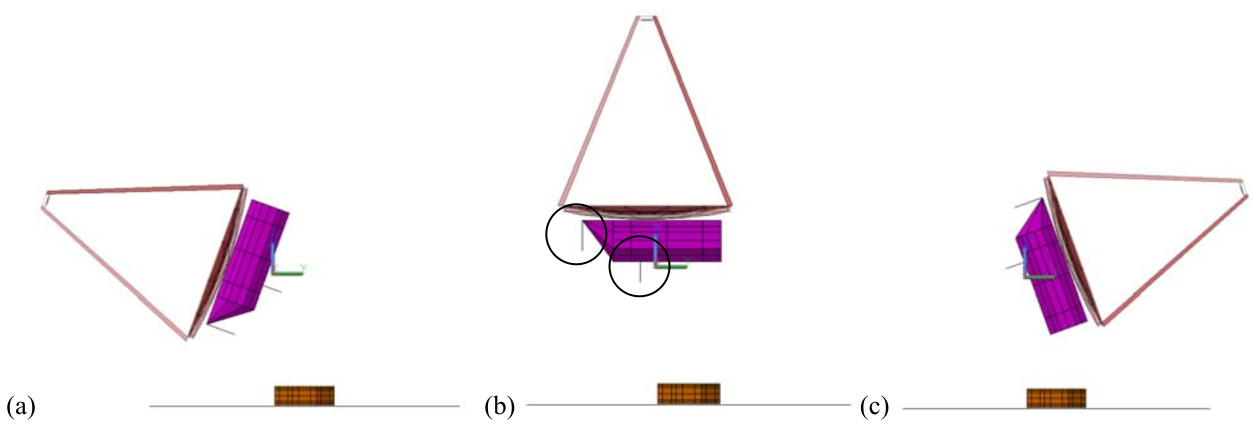

Figure 8. Payload asymmetries and offset axes of rotation (a) Telescope pitch of +70° shows an unfavorable postion for the payload raditors with there radiative view obstructed by the shield, (b) Deployable payload radiators circled, telescope pitch of 0°, (c) Telescope pitch of -70°, showing favorable positon for payload raditors with unobstructed deep space view, model courtesy of NASA/GSFC

2.3 Full Field of View - Telescope Heater Power

The field of view is extended for revisits of exoplanets and inner solar system viewing. Spacecraft pitch is utilized to reach the extended 45°of viewing area, as shown in the lightly shaded region in Figure 2. For the Normal Viewing Zone, spacecraft pitch is zero and only telescope pitch and yaw are used for viewing. For the full Field of Regard, spacecraft pitch increases up to 45°.

To visualize this data, two Veritrek ROM models were used to generate telescope heater power data (not including the spacecraft) for spacecraft pitches of -22.5° and -45°.

Figure 9 shows the total telescope power as a function of telescope pitch and yaw at a spacecraft pitch of -22.5°. The maximum power is around 3700 W and there is little variation in this value with changed pitch and yaw.

Figure 10 shows the same telescope heater power as Figure 9, but at a spacecraft pitch of -45°. There is a greater variation in telescope heater power values depending on pitch and yaw with a maximum of 3660 W and a minimum of 3520 W. Though not an order of magnitude greater, 100 W of variation at this spacecraft pitch is significantly more than that seen in Figure 9 where the power only varies by 20W.

Both plots don't follow the expected cosine trend, which again is due to the asymmetry of the payload and off axis rotation.

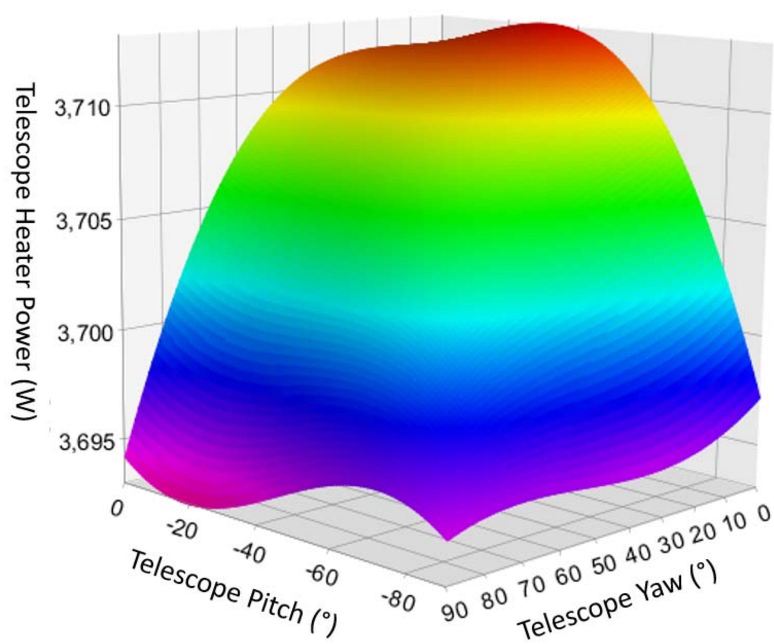

Figure 9. Telescope Heater Power with a SC pitch of -22.5°

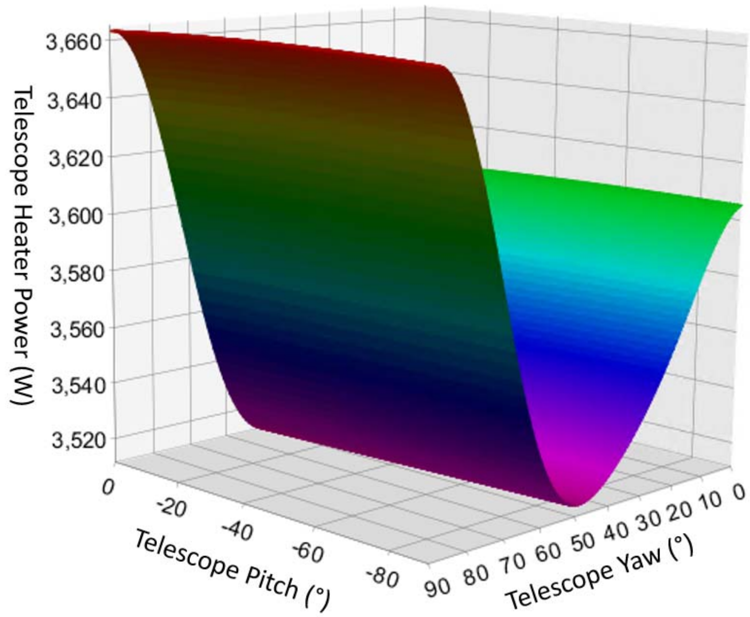

Figure 10. Telescope Heater Power with a SC pitch of -45°

2.4 Alternative Architectures

Possible options to favorably exploit the asymmetry discovered in Section 2.2 are detailed in an AIAA SciTech Thermophysics paper[5]. Options to reduce heater power in the telescope, decreasing the total size of the light shield by using a deployable Outer Barrel Assembly and/or a scarfed deployable lights shade are shown. Also, an option for having a cryogenic aft payload enclosure while simultaneously reducing heater power on the 270K telescope is presented.

3. SUN GETTER

Departing from the LUVOIR baseline concept, an innovative concept called the 'Sun Getter' aims to reduce the required total system heater power, including the spacecraft as well as the telescope assembly. This innovation uses absorbed solar flux re-radiated to the telescope for rough first stage heating. That innovation reimagines what functions a solar array can have in a large telescope architecture by combining electricity generation, stray-light control, and thermal control into one agile deployable structure[5].

3.1 Normal Viewing Zone - Total Space Vehicle Heater Power

The Sun Getter is an alternative to the baseline LUVOIR-A thermal architecture, replacing the large sunshade with a smaller, articulating solar array and enclosing the telescope in a baffle. The solar array is positioned to be normal to the sun at all positions, which shields the aft optics from stray light and direct solar heating. The solar array provides reradiated solar power from its back to the aft optics which otherwise would have come from external heaters. To reach the full field of regard, as with the baseline concept, the spacecraft rotates in pitch and roll directions in addition to the telescope rotating in the pitch and yaw directions. Roll is not called out later in this paper as it is thermally neutral. One roll position doesn't change heater power from the other. However, roll is always utilized to keep the scarf in a position to avoid sun inside the telescope barrel. While the array stays normal to the sun for all pointing positions, there is an optimal X/Y offset of the array with respect to the spacecraft as a function of the pitch and yaw angle of the telescope. The size of these offset motions can be found in more detail in another paper[7] but are on the order of 5 m in X and up to around 15 in Y. The sun getter uses a scarfed baffle around the optics which shields the telescope while allowing for the full field of regard to be viewed.

Figure 11 shows the solar view of the Sun Getter configuration as a function of the telescope pointing angle in the nominal viewing zone. Note no rotation of the spacecraft is needed in this region. Both the spacecraft and the array are normal to solar illumination.

Having a scarfed baffle around the whole telescope reduces straylight concerns and makes eliminating thermal gradients from the optics much less complex. Heater power and temperature gradients will vary more due to telescope articulations without a baffle, Figure 1, than with a scarfed baffle, Figure 11.

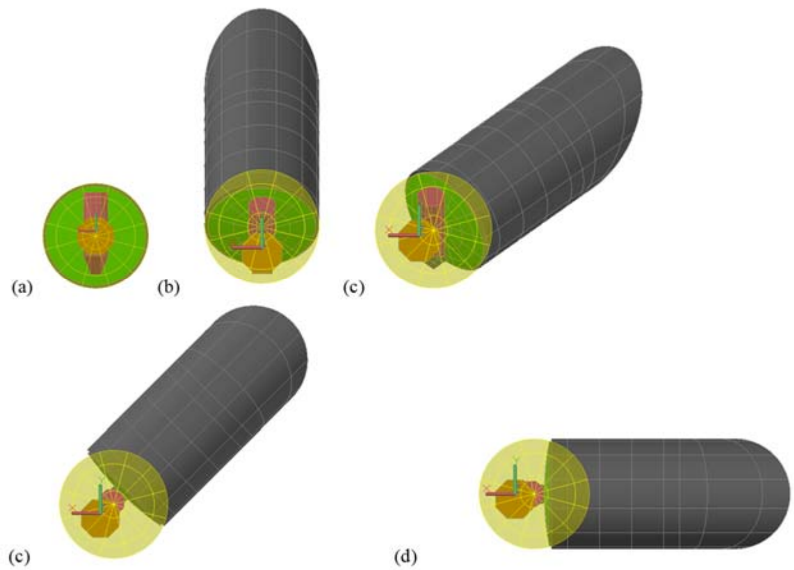

Figure 11. Sun Getter with Telescope Pitch and Yaw Movment, Solar View: a) Pitch 0° Yaw 0°, b) Pitch -45° Yaw 0°, c) Pitch -45° Yaw 45°, d) Pitch -90° Yaw 90°, Shows the sugetter and scarfed shade protecting other components from direct solar view while allowing for reradited heating

Figure 12 shows the total heater power for the space vehicle (spacecraft and telescope heater power combined) for the normal viewing zone, in the same favored quadrant that was noted in Section 2.1. Figure 12 shows a relatively flat curve with peaks when the telescope is most hidden from the sun. The highest peak in Figure 12 is at the Figure 11a configuration as there is no solar heating coming from the scarf shade.

The 3D surface plots of total power as a function of pitch and yaw are generated using MATLAB plotting software from Thermal Desktop results. Each coordinate in MATLAB corresponds to the total power for the given pitch and yaw position. A surface is created from discrete points using MATLAB's interpolation function with the natural neighbor interpolation method. This interpolation method is the smoothest of all MATLAB's available methods and it generates a large grid of data which can be used to create the 3D surface contour.

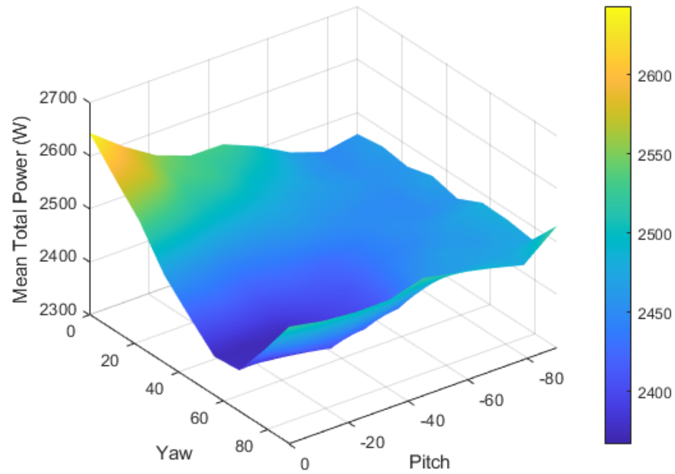

Figure 12. Total Space Vehicle Heater Power with Sun Getter, Spacecraft Pitch 0°

3.2 Full Field of View - Total Space Vehicle Heater Power

Figure 11 shows a side view of the Sun Getter observing the normal viewing hemisphere and the extended viewing region. In the extended region, the Sun Getter is positioned to absorb the maximum amount of direct solar energy (still normal to solar flux with X/Y offset calculated as in reference 7) but both the telescope and spacecraft rotate to the desired pointing.

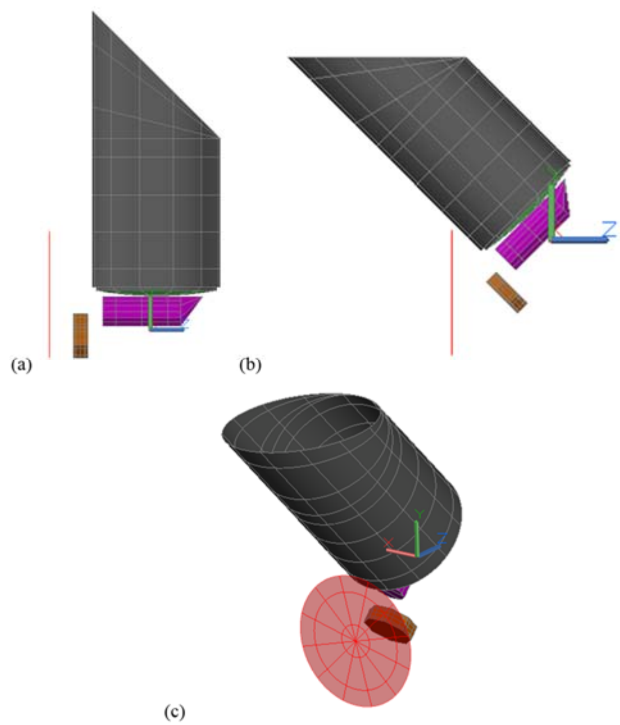

Figure. 13 Telescope Articulation to Inner Solar System Region and Corresponding Sun Getter Adaption to block direct solar energy (a) Telescope pitch -90°, yaw 0°, Spacecraft pitch 0° (b) Telescope pitch -90°, yaw 0°, Spacecraft pitch -45° (c) Telescope pitch -90°, yaw 0°, Spacecraft pitch -45°, Isometric View

Figures 14 and 15 show the total heater power for the space vehicle for the extended viewing zone. Figures 6, 9, and 10 showing telescope heater power for the baseline LUVOIR concept can be compared with Figure 12 – 15 that show total space vehicle power using the Sun Getter with one important distinction. Figures 12 – 15 include spacecraft power and Figure 6, 9, and 10 are only for the telescope assembly. Even with that addition, the predicted total heater power is dramatically lower with the Sun Getter.

Another interesting observation was made while creating the models to extend the Field of Regard from the Normal Viewing Zone to the Inner System and Exoplanet Zone. Many possible combinations of telescope pitch and spacecraft pitch exist for imaging a given point. For example, a hypothetical science observation point is located at a point with a pitch of -10° and yaw 0°. One could position the telescope at null, 0° pitch and 0° yaw and pitch the spacecraft -10°. Or pitch the telescope 1° and the spacecraft 9°, etc. When considering total space vehicle heater power, not just telescope heater power, Figures 12 – 15 show us that pitching the telescope is always favorable over pitching the spacecraft. This could be important for designing ground commands and logic that conserve system resources for a future observatory like LUVOIR.

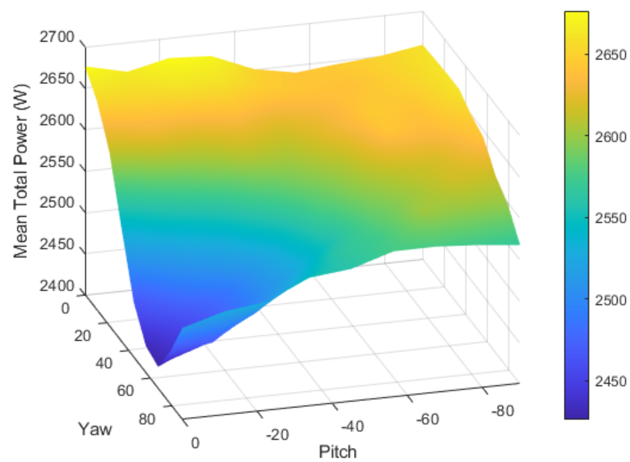

Figure 14. Total Space Vehicle Heater Power with Sun Getter, Spacecraft Pitch 22.5°

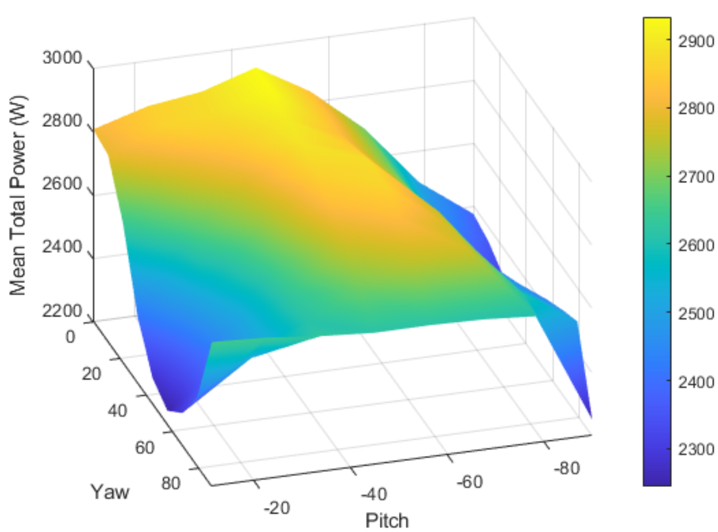

Figure 15. Total Space Vehicle Heater Power with Sun Getter, Spacecraft Pitch 45°

4. CONCLUSIONS

Starting with a conceptual thermal model of LUVIOR-A, provided by NASA/Goddard Space Flight Center, alternate concepts of operations were explored. A quadrant within the Normal Viewing Zone was shown to bring the maximum heater power required for a 270K telescope down by almost 200 W. Asymmetry within the telescope geometry and the axes of rotation were shown to be beneficial for reducing telescope heater power and ensuring instrument radiators stay at temperature. A candidate technology, The Sun Getter, was identified that uses solar power for rough first stage heating. This reduces the total heater power for the space vehicle including the spacecraft and the telescope assembly by around 2000 W comparing max cases of the baseline shown in this paper and The Sun Getter. Finally, nuances of extending the Field of Regard from the Normal Viewing Zone to the Inner System and Exoplanet Zone showed pitching that the telescope reduced heater power compared to pitching the spacecraft, a maximum reduction of 450 W was seen.

REFERENCES

[1] Paul A. Lightsey, Charles B. Atkinson, Mark C. Clampin, Lee D. Feinberg, "James Webb Space Telescope: large deployable cryogenic telescope in space," Opt. Eng. 51(1) 011003 (3 February 2012)

[2] "LUVOIR Final Report," https://asd.gsfc.nasa.gov/luvoir/reports/ (August 26, 2019).

[3] Thermal Desktop Software Package, Ver. 6.1, Cullimore and Ring Technologies, Boulder, CO 80302, 2020.

[4] Veritrek Software Package, Ver. 3.2, Veritrek, Denver, CO, 2020.

[5] Bannon, E., Weed, K., Knight, J. S. and Coyle, L., "Architectures to Reduce Heater Power for Large Space Telescopes," AIAA SciTech Adaptive Structures Conference, 2022.

[6] Bannon, E., Weed, K.., and Knight, J. S., Ball Aerospace and Technologies Corp., CO, U.S. Patent Application for "Multiple Function Spacecraft Sunshade Systems and Methods," Application Serial Number 17/224,863, filed 7 April 2021.

[7] Bannon, E., Weed, K., Knight, J. S. and Coyle, L., "Adaptive Solar Array Sun Shield Heaters for Large Space Telescopes," AIAA SciTech Adaptive Structures Conference, 2022.