Astro2020 White Paper for State of the Profession Considerations

Ultra-stable Technology for High Contrast Observatories Decadal Whitepaper

Relevant to High Contrast Systems, Ultra-stable Systems and Exoplanet Science

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1.0 Summary of the Issue

One of the key challenges for the field of Astrophysics is to survey a large number of Sun-like stars with Exo-earth candidates to determine if there are spectral signatures consistent with life. There are two major ways to achieve this. The first is to use large starshades and the second is to use internal coronagraphs with large stable telescopes. While an internal coronagraph has the potential to provide a very efficient way to survey a large number of stars, the key challenge identified is the stability required for these observations. More specifically, a large space telescope that uses an internal coronagraph to obtain spectra of earth-like planets in the habitable zone around other stars will require a contrast of 10^10 to block out the bright star and an associated contrast stability of 10^11 to assure the primary mirror stability is not confused with the exo-earths. Several groups have shown that for the LUVOIR segmented design using the proposed coronagraphs (see whitepaper by Pueyo) the wavefront stability needs to be in the 10's of picometers RMS wavefront and the tightest requirements are the piston, tip and tilt of individual segments. Work assessing the LUVOIR requirements by Juanola-Parramon/SPIE 2018 shown below in Figure 1 shows a LUVOIR-A with APLC coronagraph would require 10-20 picometer segment to segment piston and tip/tilt wavefront stability. These required levels are significantly beyond what has been done in the past. In this whitepaper we address the feasibility and confidence of achieving these requirements and important next steps. This assessment is based on a series of studies and technologies we have undertaken for nearly a decade including recent progress on picometer level stability measurements and control demonstrations.

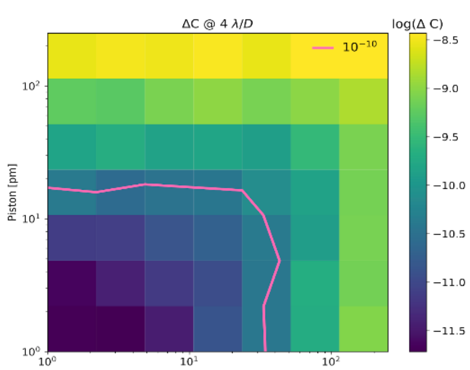


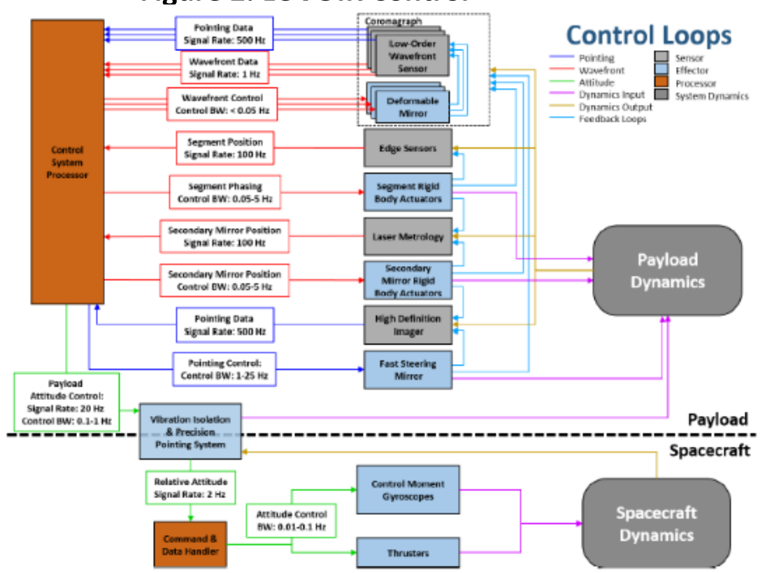
Figure 1: Picometer Stability: Key Driver for Segmented Systems

2.0 Strategy Considerations

For this whitepaper, we will focus on segmented systems for LUVOIR though much of the results are also applicable to monoliths (the primary difference being that segmented systems are driven by the piston, tip, tilt stability of segments while monolith systems envisioned for space applications are driven by mount induced trefoil and gravity actuator induced distortions whose spatial frequency content fall within the IWA to OWA).

The LUVOIR architecture was developed to address the overall 10-20pm wavefront stability requirement through the use of a multi-tier stability control system including nested loops for line of sight and wavefront. The stability requirement is primarily on the primary mirror where the picometer stability requirement occurs and can be further broken between mirror segment and then segment to segment variations (which can be actively controlled). The control architecture envisioned is not set-and-forget like JWST, but rather a dynamic, active control system with nested and overlapping WFE and line-of-sight (LOS) control. High frequency dynamic disturbances are controlled through non-contact isolation (eg, voice coils) between the telescope and spacecraft and the feasibility of this approach has been shown by scaling and integrated modeling (Feinberg/SPIE 2016). The primary requirement is on the primary mirror system itself which is at the pupil which is also the largest system, other elements of the telescope have significantly relaxed requirements. To build a large primary mirror of this level of stability, even with this overall architecture one needs the constituent components (mirror segments, backplane, control) to be adequately stable and that is the key emphasis of the work and strategy described here.

Figure 2: LUVOIR Control



2.1 Mirror Segments

The key requirements for stable mirror segments are to make the mirrors sufficiently stiff for dynamics and to make them thermally stable based on material choice and heater design. The segment diameter and stiffness was chosen to assure that mirror dynamic deformation modes are not a concern (based on scaling and modeling demonstrated in Feinberg/SPIE 2016). Optodynamics of Webb mirrors measured at the picometer level (Saif/Applied Optics/2017) showed that mirrors deform possibly due to inertial reaction against mounts but this effect can be made small enough through adequate mirror stiffness and with limits on rigid body motions.

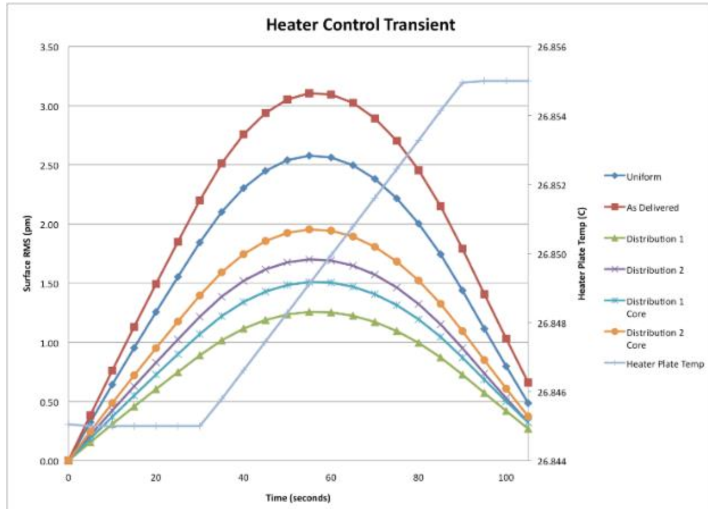


Figure 3: Heater Cycling Transient Analysis of the ULE mirror

To minimize thermal expansion and contraction of mirror segments that would negatively affect wavefront stability, an ultra-stable thermal environment has been designed based on parametric studies done on ULE segments (Reference: Eisenhower et. al. SPIE 2015) and this approach was implemented in LUVOIR designs. The approach described by Eisenhower uses a heater plate immediately behind a mirror substrate, radiatively heating a mirror substrate. Due to its extraordinarily low coefficient of thermal expansion at that nominal operational temperature, the team studied Corning's Ultra-Low Expansions (ULE®) titania-silicate glass which is built as a closed back mirror that can meet the stiffness need. As shown in Figure 2, heater cycling transients were studied parametrically using a notional and arbitrary heater pulse frequency and magnitude peak-to-valley (P-V) excursions of +/-5mK. The dynamic steady state optical response just due to the heater cycling and with various values of CTE distributions resulted in **Surface Figure Error varying between 1.3 pico-meter (pm) and 3.1pm RMS at peaks** (Figure 3). A reduction in cycling time and/or a reduction in heater plate temperature excursions would reduce the response even further. These results give confidence that mirrors of picometer level thermal stability are feasible with milli-Kelvin type thermal control (and which has now been demonstrated at small scale as discussed later).

2.2. Backplane

The LUVOIR type mission relies on a combination of advanced active controls to deal with large environmental influences and structure passive characteristics to maintain stability between updates. The ULTRA study performed by an industry team led by Ball Aerospace demonstrated material systems like those applied to JWST combined with the planned active controls will be adequate for a LUVOIR type mission (Ultra study report/2019). Findings from that effort suggest that CTE control on the order of 5 ppb/K and temperature control on the order of 2 mK will be a reasonable balance of the challenge between material and control system design spaces. Compared to JWST material control shown in Figure 4, material CTE characterization and acceptance for LUVOIR class error budgets needs 10x improvement from the JWST methods without compromising capacity and rate. Efforts to achieve this improvement are underway by addressing the electronics used in making the measurements. This is considered a feasible improvement and more active control of the primary would make this not even necessary.

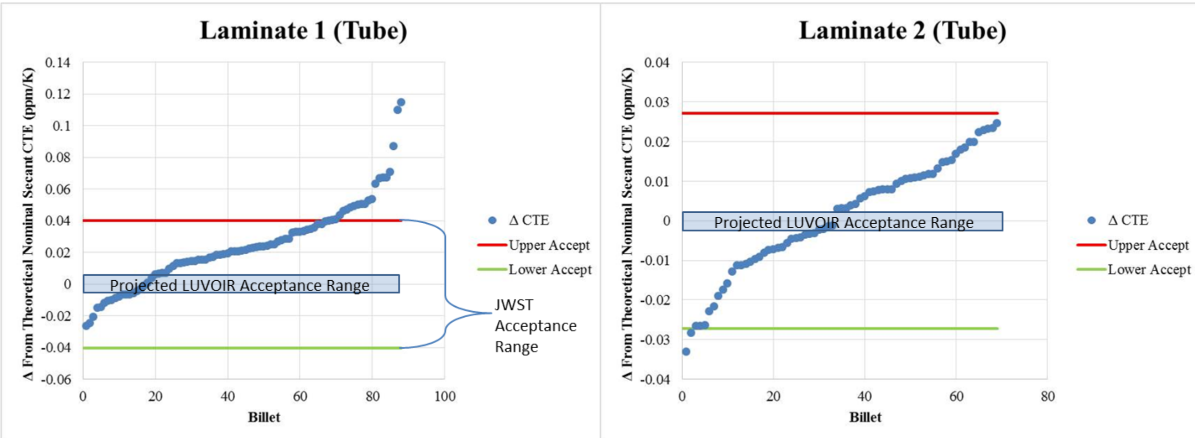


Figure 4: JWST data shows that some structural elements met the stringent control projected for LUOVIR type missions. Advances in material production control and component verification accuracy are necessary advances for LUVOIR type missions.

The contribution of non-controllable effects (short of active methods) such as moisture dry-out in composites was also evaluated. A threshold strain rate level of 10^{-10}/hr can be considered insignificant to the wavefront error budget accounting. Furthermore, a combination of design and operational concepts can be struck that suggest the lower strain rate is achievable by practical and available means. This approach includes limiting components of high stability influence to wall thicknesses less than 1.6 mm which is in line with most structural elements in the JWST backplane. This design constraint in combination with a 100-day dry-out time on orbit during transit and commissioning is enough to eliminate the risk of moisture effects as shown in Figure 3.

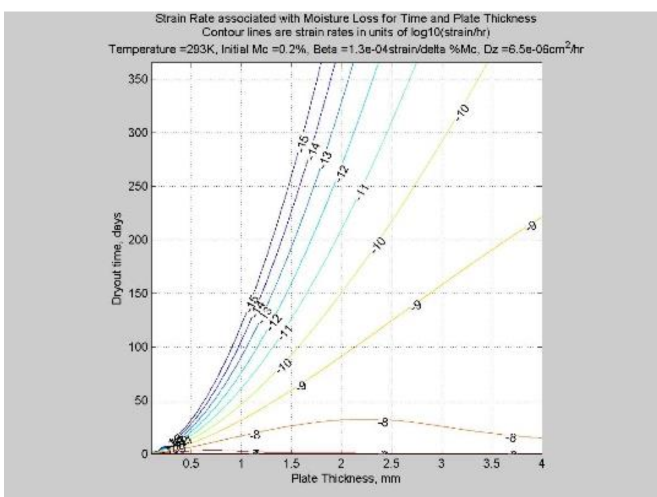


Figure 4: Preliminary evaluations of moisture strain rates suggest a practical and plausible design space is available that does not require significant advancements in material

capabilities.

In summary, a LUVOIR type mission with existing precision material systems like those used on JWST and preceding space telescopes is feasible. Improvements in manufacturing efficiency and metrology for component level verification and acceptance are key to support the cost and reliability elements of the mission.

As a part of the LUVOIR conceptual architectural studies, we undertook a backplane level thermal distortion study (Reference: Park et. al. SPIE 2017) to guide the thermal architecture of the carbon fiber composite backplane. When combined with a precision milli-Kelvin scale thermal control system and a near-zero CTE composite materials, a picometer class thermal-elastic stability performances was shown to be achievable. A thermal-distortion study was methodically performed in a manner to isolate individual heater control locations within the structural members of backplane assembly. This study showed the sensitivity to the heater control locations that may impact the systems-level wavefront error due to rigid body motions of the primary mirror segments. This study also assessed the systems-level WFE sensitivity due to the composite CTE and its variability at various locations within the backplane structure assembly.

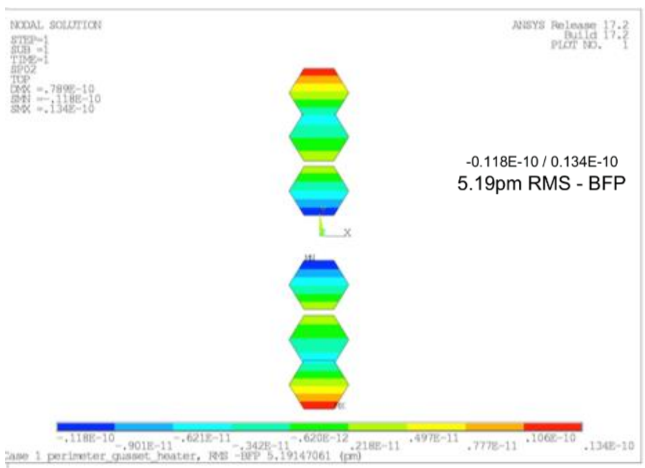


Figure 5: SFE calculation with multi heater zones backplane

The results from the thermal model predictions with thermal gradients were then mapped on to the FEM and solved for SFE. The multi-heater zones case showed that the **SFE with Best-Fit-Plane (BFP) removed resulted in roughly 5.2 pico-meter RMS**. Again, this analysis was performed in a purely thermal steady state conditions with a 1mK heater offset. However, it is expected that a future transient analysis would show a smaller SFE value when considering the thermal mass of the system. If active controls are employed (eg, edge sensors and actuators as baselined for LUVOIR), these effects would be removed actively and this would represent the dynamic range and could be relaxed significantly.

Dynamically, backplanes dynamic effects need to be controlled through system. These effects were included in the LUVOIR integrated models and shown to be feasible. The stiffness of the backplane is related to its design which itself is related to mass. In principle, stiffer backplanes are feasible with sufficient volume and mass and will require optimization during the architecture phase of a mission and an argument for protecting mass and volume reserve.

2.3 Metrology and Control Demonstrations

While the analyses discussed in sections 2.1 and 2.2 are based on coupon and material data, a key question is can we even measure picometer spatial changes of actual segments and systems and are built up systems stable to picometer levels. Our team recognized the possibility of performing spatial metrology to the picometer level during optodynamics analysis measurement of JWST mirror segments so that is the starting point for this discussion. Previously published work from JWST documented an evaluation of a PMSA segment response when subjected to low-level micro-dynamic disturbance (Saif/Applied Optics/2017). The test was accomplished using a High Speed Interferometer (HSI) to interrogate the mirror surface while applying a controlled sinusoidal input to the supporting structure. The test results from a JWST segment is shown in Figure 6 and showed the ability to sense sub-nanometer contributions in the higher order Zernike terms at different frequencies and was the first indication that picometer spatial sensing was feasible. Figure 5 shows the level of predictability with conventional modeling methods is respectable to build confidence our linear dynamic modeling could assess picometer stability to the magnitude level.

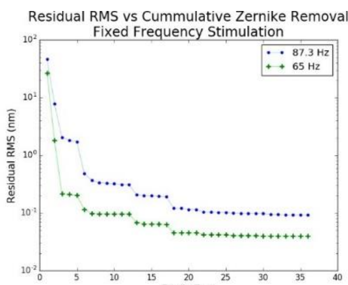


Figure 6: JWST PMSA micro-dynamic testing illustrates the existing ability to accurately sense and quantify sub-nanometer spatial contribution to mirror figure pertubations.

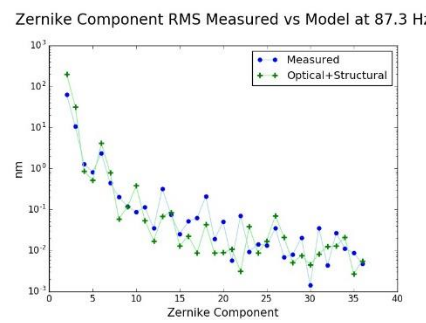


Figure 7: Zernike content in the PMSA under micro-dynamic loading is predictable to sub-nanometer levels using conventional modeling methods.

The results from the Webb systems provide an indication that specular measurements are feasible in terms of resolution and this methodology was used to measure an actuator discussed later. However, to make direct measurements of the building blocks of ultra-stable systems (coupons, bonds, joints, materials, etc), the next step was to develop a custom High-speed electronic speckle pattern High Speed Interferometer (HSI) to measure the vibrational and thermal induced responses of diffuse surfaces. This has the advantage of not requiring corner cubes that would need to be

Figure 8: Custom HSI demonstrated sensing of dynamic effects and motions at picometer scale and accuracy.

mounted and provides surface deformations directly. This HSI, shown in Figure 8, is capable of capturing surface measurements at a rate greater than 2 KHz, three orders of magnitude faster than traditional temporal phase shifting interferometers. Three cutting edge technologies were combined to achieve such a high image acquisition rate.

1. A dynamic spatially phase-shifted interferometer
2. A high-speed low noise CMOS camera
3. A high-power, long coherence laser

Specular and diffuse specimen surfaces were subjected to known dynamic motion ranging from 12 pm to 100 pm. The HSI was used to track and record the motions and demonstrated agreement with the controlled input to < 2 pm for a specular mirror surface (no speckle) and <4 pm for the diffuse composite surface.

The measured surface was decomposed into Zernike components. The evaluation showed that reliably detecting effects at sub-pm scales is achievable, which indicates the practicality of evaluating higher spatial models in mirror segments. Table 1 shows the results of this decomposition for the diffuse composite specimen.

Table 1 – Tabulated outcome of the surface analysis results from both test campaigns at 20 pm amplitude.

	First Set – 8K runs			Second Set – 21K runs		
Surface Zernike Term	Amplitude (pm)	Standard Deviation (pm)	Probability of Null	Amplitude (pm)	Standard Deviation (pm)	Probability of Null
Z0	15.34	1.624	0.0000	13.84	3.456	0.0003
Z1	0.16	0.032	0.0000	0.12	0.062	0.1674
Z2	0.10	0.076	0.4400	0.30	0.112	0.0026
Z3	0.11	0.021	0.0000	0.10	0.037	0.1787
Z4	0.05	0.013	0.0005	0.04	0.018	0.0687
Z5	0.05	0.014	0.0049	0.04	0.020	0.0784
Z6	0.02	0.009	0.1800	0.00	0.011	0.0922
Z7	0.02	0.010	0.1200	0.01	0.012	0.8052
Z8	0.02	0.010	0.2800	0.01	0.011	0.5089
Z9	0.02	0.011	0.3100	0.04	0.014	0.0240

Figure 9: Vendor Data for 5pm step actuator, NASA results for 40Hz (left) and vendor data showing 1.5pm agreement (right)

In support of these measurements, a closed loop piezo actuator was used to provide a calibration source by creating a sinusoidal motion in the test specimen. One of the surprising outcomes of this calibration work was that the actuator chosen was able to consistently move in 5 picometer steps and could be modulated at high enough speed to correct drifts and even low frequency changes in segments. The actuator had previously been calibrated using Atomic Force Microscopy at the vendor. NASA measured the actuator connected to a spherical mirror modulated with a sinusoid at 40Hz and the data was compared against the vendor reported result and the two results matched to within 1.5pm in an absolute sense. This not only provides a useful calibration method that was used to show metrology resolution but demonstrates the power of closed loop piezo control to remove instabilities. The actual actuator had multiple micron stroke and could be connected to a nanometer step actuator like those used on JWST to provide the fine level resolution of a segment or could be part of an array of small mirrors at a correcting pupil.

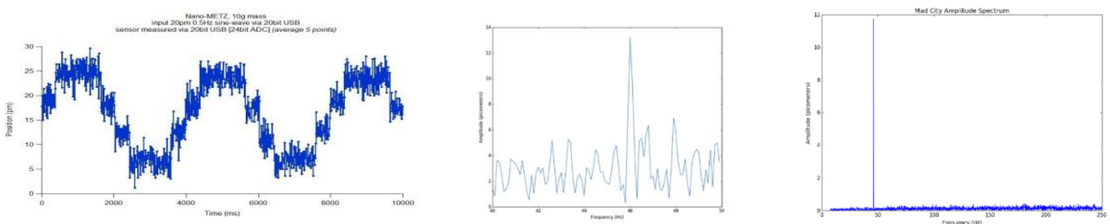


Figure 9: Vendor Data for 5pm step actuator, NASA results for 40Hz (left) and vendor data showing 1.5pm agreement (right)

In addition to this recent test data, our team data mined 24 hours of speckle interferometry from the Backplane Stability Test Article (Saif/2008) which is a $1/6^{th}$ scale composite subscale test article of the Webb backplane that was tested at 45K. The original measurement showed nanometer level changes with small deviations in the operating temperature and our new analysis of the data shows that the uncertainty of our speckle measurement was in 10's of picometers and this was an environment that was not ultra-stable. This gives us confidence that when we use high speed methods (not just many short exposures) and an ultrastable environment, we can perform metrology on large backplane structures to picometer levels. Also, had there been large unstable dynamic deformations, we would not have achieved this result.

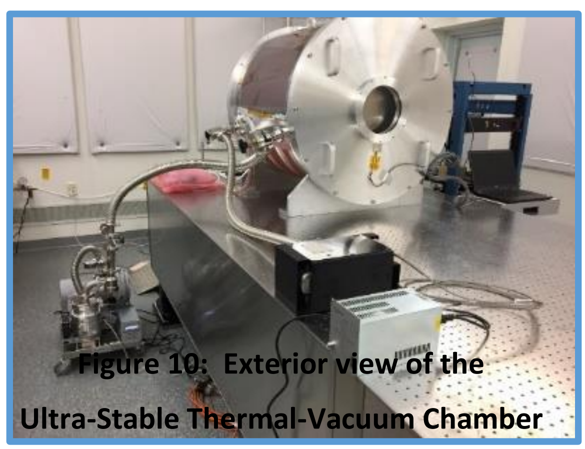


Figure 10: Exterior view of the Ultra-Stable Thermal-Vacuum Chamber

Many of the challenging design requirements for ultra-stable performance create challenging requirements for test facilities and ground support equipment, which may very well need to be more stable or sensitive than the flight hardware under test in order to verify system performance. LUVOIR's ultra-stability requirements will demand micro-gravity-level vibration isolation and sub-milli-Kelvin level thermal stability. As part of a milli-Kelvin active thermal control demonstrator, we developed the design, manufactured, and assembled a thermal vacuum test chamber system. This vacuum chamber 30” diameter x 30” long with an optical window, thermal controller, heaters and associated electronics to accommodate an optical test article in support of the picometer stability investigations.

The final functional test of this chamber resulted in the achieved average surrogate test article thermal stability +0.0004/-0.0002C over 80+ hours (+0.4mK / -0.2mK) with the 23.5°C nominal set point. This validation test data was gathered while the local lab ambient temperatures varied between 18.5 and 22.0°C.

Further to the ultra-stable chamber development, an Ultra-Stable Picometer-Scale Mirror Assembly was developed. This assembly mimics the ultra-stable mirror thermal control architecture as described earlier. It a heater plate and a ULE single substrate that would be actively controlled to a milli-K level stability.

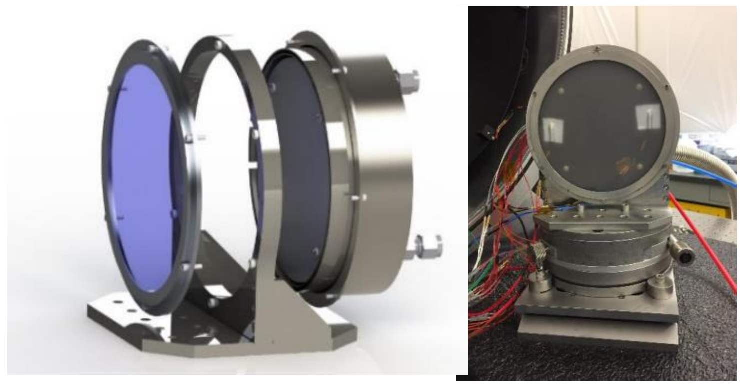


Figure 12: Solid-model and actual images of the Ultra-Stable Picometer-Scale Mirror Assembly

The final functional test of the ULE test article resulted in a thermal stability of 0.6mK P-V over 4+ hours at the ULE mirror substrate.

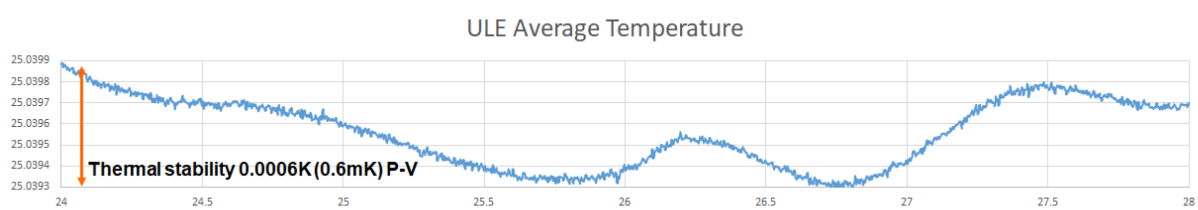


Figure 13: Results of the final functional test of ULE Mirror substrate showed the thermal stability of 0.6 milli-K P-V over 4+ hours

While larger scale demonstrations are needed, these achievements demonstrate the feasibility of the milli-Kelvin scale thermal sensing and control.

A key question that is currently being tested is long term drift of thermally controlled mirrors and structures. Drift is more difficult to measure due to environmental considerations but our work has demonstrated that the components of drift are understood and can ultimately be sufficiently controlled. The main driver for actual mirror or structure drift is expected to be the stability of the electronics that control the heaters (this is due to the isolated nature of the architecture). Long term heater demonstrations show this is feasible over 10’s of minutes but more work is needed, some of which will occur soon. In addition, structural drift can be controlled by active control (eg, edge sensors) or by slowing it down through thermal mass and ultimately drift will drive the technology selection for the sensing of the active systems and there are several options.

2.4 Active Control:

While several groups have started to demonstrate edge sensing and laser metrology methods for providing drift control of segments to the levels needed for LUVOIR, one possible outcome of the work discussed here is a system in which the HSI is the sensing source and picometer motion actuators as discussed in these results are used. In that case, both the sensing resolution and control resolution have been demonstrated. One way to implement this is to put the interferometer at center of curvature (or send collimated light to a periscope with a null). This would require a boom essentially twice the length of the secondary mirror deployment system but would not require ultra-tight alignment stability. This approach would be fully active and could be verified subscale on the ground. The key challenge that would be new would be to do the computation of segment motions in real time. Alternatively, this type of architecture could be used to characterize an active primary mirror for verification purposes. Lessons learned from the passively stable Webb telescope suggest that an active system of this nature is highly attractive to study to simplify verification but the approach requires early resources to determine what is fully feasible before the architecture is locked into place.

3.0 Organization, Partnerships and Current Status

Significant progress has been made in defining the required stability needed for future large segment space telescopes. These studies have shown that segment tip, tilt and piston are driving requirements. Significant work has shown by analysis that architectures can address these demanding requirements that properly isolate vibration, thermally control mirrors and backplanes, and control residuals. A sequence of experiments has shown that the metrology to support this is feasible, actuators can move at these levels, joints can be made that are stable, and mirrors can be thermally controlled to the needed levels. More work is needed to address longer term drifts and to scale to larger sizes but the analysis and component tests that address the set of challenges for a large segmented primary mirror with picometer stability have been assessed and all aspects have shown a level of feasibility.

If the Decadal panel moves forward with a recommendation for an observatory requiring ultrastability, it will be critical to invest heavily in the various technological solutions to address ultrastability in parallel with iterating architectures early on before a large marching army comes aboard. Given the challenging requirements discussed, it's likely that overlapping passive and active methods will be employed and the key will be choosing technologies that are implementable and cost effective. To date, the work described here has been funded primarily through ROSES SAT funding. Early JWST mirror and backplane investment required 10's of millions of dollars and the infrastructure of a project and support team. NASA provided the overall leadership and test capabilities and industry provided the studies and technologies and then ultimately built the telescope. This very successful model can be employed using an experienced team but that opportunity will go away if it is not prioritized in this decadal.

Building a large telescope typically starts with the primary mirror. Building a large primary mirror starts with the hardest technological challenge. In this case, the hardest challenge is the ultrastable structures, optics, sensing and control. A significant investment in this area along with parallel architecture and coronagraph investments will result in a mature design that can be built with the least number of iterations and for the least amount of money. If the goal is ultimately to perform a large survey of Exo-earths that could bear life, then prioritizing this investment and doing it aggressively will be critical to assure success.

In terms of priorities, a good way to think about the investment in the area of ultra-stable telescopes that can help NASA detect signs of life is to consider what would happen if there isn’t a major investment in this area. In that case, there would be a decade long gap and there will be a significant loss of corporate memory and momentum. At that point, the US will have lost its edge towards the next major advancement in large space telescopes and NASA will have essentially taken a large step back in its overall goal of finding life.

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