Fast steering mirror disturbance effects on overall system optical performance for the Large Ultraviolet/Optical/Infrared Surveyor (LUVOIR) concept using a non-contact vibration isolation and precision pointing system

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ABSTRACT

As the optical performance requirements of space telescopes get more stringent, the need to analyze all possible error sources early in the mission design becomes critical. One large telescope with tight performance requirements is the Large Ultraviolet / Optical / Infrared Surveyor (LUVOIR) concept. The LUVOIR concept includes a 15-meter-diameter segmented-aperture telescope with a suite of serviceable instruments operating over a range of wavelengths between 100nm to 2.5um. Using an isolation architecture that involves no mechanical contact between the telescope and the host spacecraft structure allows for tighter performance metrics than current space-based telescopes being flown. Because of this separation, the spacecraft disturbances can be greatly reduced and disturbances on the telescope payload contribute more to the optical performance error. A portion of the optical performance error comes from the disturbances generated from the motion of the Fast Steering Mirror (FSM) on the payload. Characterizing the effects of this disturbance gives insight into the specifications on the FSM needed to achieve the tight optical performance requirements of the overall system. Through analysis of the LUVOIR finite element model and linear optical model given a range of input disturbances at the FSM, the optical performance of the telescope and recommendations for FSM specifications can be determined. The LUVOIR observatory control strategy consists of a multi-loop control architecture including the spacecraft Attitude Control System (ACS), Vibration Isolation and Precision Pointing System (VIPPS), and FSM. This paper focuses on the control loop containing the FSM disturbances and their effects on the telescope optical performance.

Keywords: Optical performance, fast steering mirror, LUVOIR, disturbance sources, segmented primary mirror

1. LUVOIR MISSION CONCEPT AND TELESCOPE STABILITY

The Large Ultraviolet / Optical / Infrared (LUVOIR) Surveyor concept mission is one of four Decadal Survey Mission Concept Studies with ambitious design and science goals to enable advances across a broad range of astrophysics.[1] LUVOIR as discuss in this paper consists of a 15-meter-diameter segmented-aperture telescope with four serviceable instruments; ECLIPS (Extreme Coronagraph for Living Planetary Systems), HDI (High Definition Imager), LUMOS (LUVOIR Ultraviolet Multi Object Spectrograph), and Pollux, a CNES-led and ESA-consortium contributed instrument concept for a high-resolution UV spectro-polarimeter. The instruments used to achieve the science goals require an ultra-stable platform to operate and perform. One requirement that stems from the science goals is the wavefront error (WFE) stability needs to be less than 10 picometers RMS of uncorrected system WFE per wavefront control step. This paper describes how one disturbance on the payload can affect the overall optical performance of the observatory in addition to recommendations for reducing the effect of this disturbance.

1.1 Control Architecture for Telescope Pointing

The LUVOIR observatory has two elements, the payload and the spacecraft. The spacecraft includes the spacecraft bus and the sunshade. The payload element includes the optical telescope assembly (OTA), the four instruments, and the Payload Articulation System (PAS). The PAS comprises two gimbals for articulating the payload relative to the spacecraft, and the Vibration Isolation and Precision Pointing System (VIPPS), which is used to reduce the disturbances from the spacecraft via a non-contact isolation system.

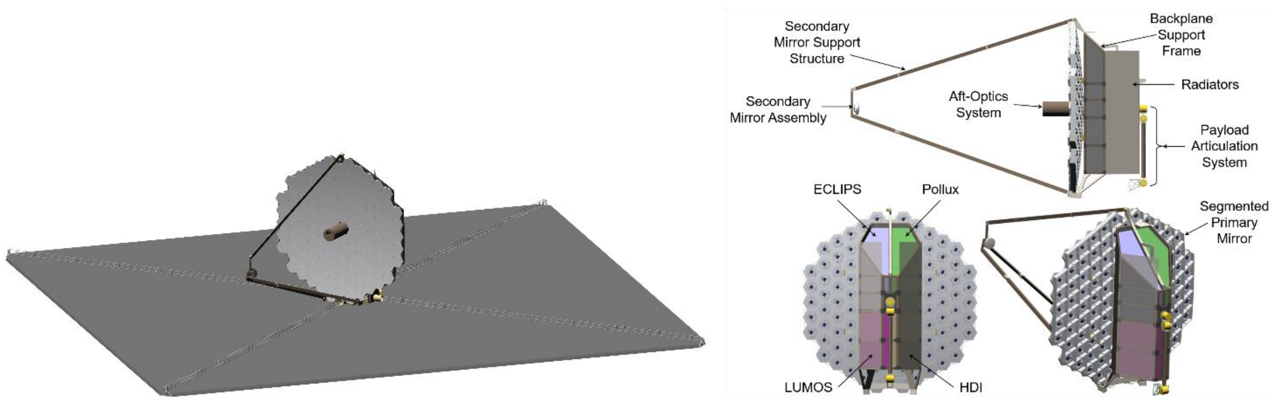

Figure 1: The LUVOIR observatory. The spacecraft bus is located below the sunshade while the PAS runs between the spacecraft and the payload. The figure on the right is only the payload with the OTA components.

Much of the payload used to achieve the science goals consists of stationary components. One non-stationary component on the payload is the Fast Steering Mirror (FSM). This component is used in the multi-loop control architecture shown in Figure 2 to offload higher frequency line-of-sight pointing errors in the payload. The FSM is one of the largest disturbances on the payload side of the observatory. This paper will focus on the FSM disturbance influence on the motion of the payload elements.

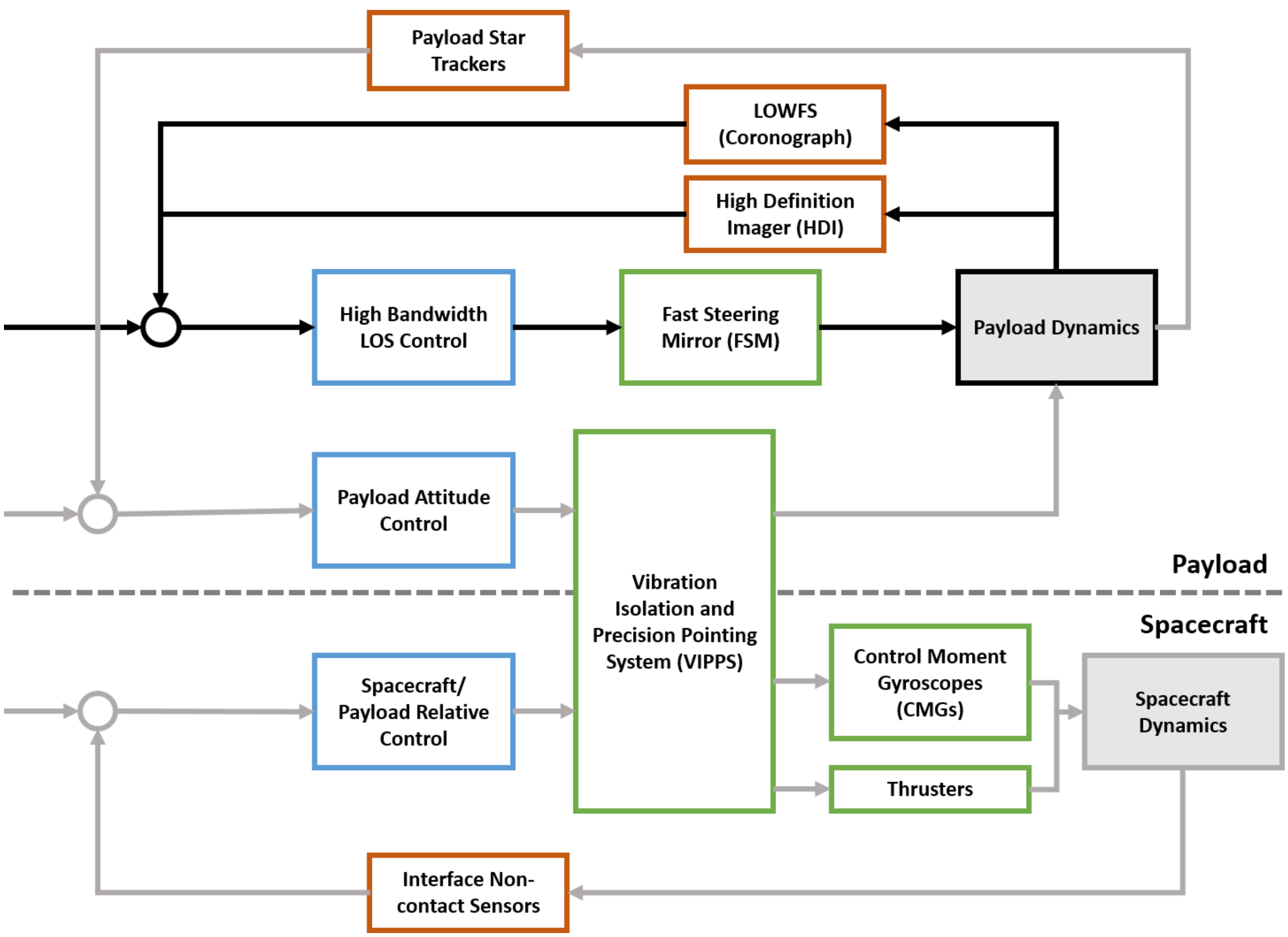

Figure 2: The multi-loop control architecture includes the FSM control loop, Payload attitude control loop, and Spacecraft/Payload relative control loop. The FSM loop is shown with a black line, while the ACS control loops are in gray.

2. LUVOIR INTEGRATED MODEL

One way to analyze and predict the optical performance of large telescope systems is to create an integrated model. Integrated modeling is creating an overall input-output system model comprised of models from different disciplines. The models used in the LUVOIR integrated model include structural, optical performance, and disturbance models. A finite element model (FEM) is used to assess the dynamic response of the system being characterized. Modeling the performance of an optical system like LUVOIR can be accomplished with a linear optical model (LOM) to express the optical performance as a linear combination of the optical displacement and rotation of specific nodes in the FEM. Good practice when using a FEM and LOM in an integrated model is to have all of the nodes in the FEM be placed at the same locations as the optical nodes in the LOM. The integrated model used for this analysis is made up only of the payload components necessary to assess how the disturbances from the FSM propagate through to the optical performance.

2.1 LUVOIR Payload Finite Element Model

This paper focuses on the payload element of the LUVOIR observatory. The FEM of the LUVOIR primary and secondary mirror assemblies is shown in Figure 3. The primary mirror assembly consists of the primary mirror backplane support structure (PMBSS), 120 primary mirror segments, and the aft optics system (AOS). The PMBSS is the frame type structure supporting the primary mirror segments and it consists of standard plate and beam elements.

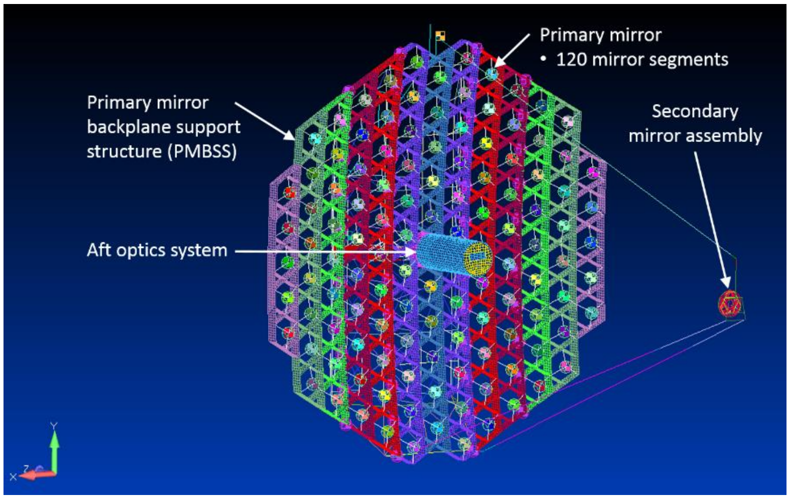

Figure 3: LUVOIR Primary and Secondary Mirror Assemblies Finite Element Model

Each primary mirror segment is modeled using a mass element connected to an optical node which is located at the center of the optical surface of each segment. The optical nodes are used in the linear optical model (LOM) to calculate disturbances in the optical performance due to disturbance inputs injected into the structure at different locations in the structure.

The mass element in each segment is coincident with a spring element which then attaches to the backplane structure using a rigid body element (RBE). The rigid element is a NASTRAN RBE3 which uses interpolation to calculate the motion of the segment node from the motions of the three backplane nodes to which it is attached. The FEM of a primary mirror segment is shown in Figure 4a. The spring element stiffness and mass element inertia provide inertia and stiffness values comparable to flight heritage mirror segments used on the James Webb Space Telescope (JWST) observatory.

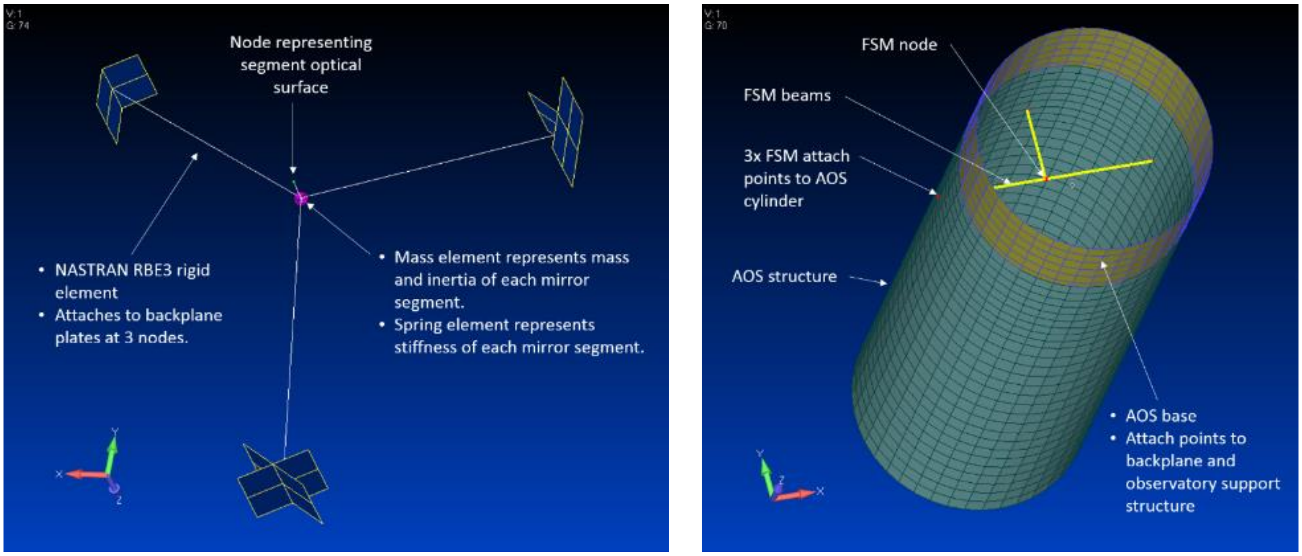

Figure 4: Individual payload structures. a) LUVOIR primary mirror segment finite element model. b) LUVOIR aft optics system finite element model.

The FSM is housed inside the AOS cylinder and the FEM of the assembly is shown in Figure 4b. The FSM is modeled using beam elements attached directly to the walls of the AOS in three places. The structure of the AOS is modeled using plate elements. It is rigidly attached to the PMBSS and the observatory backplane support structure (BSF) using NASTRAN RBE2 elements. The AOS is connected to the backplane through these rigid elements, so any disturbance injected into the FSM node will propagate through the rest of the primary mirror assembly.

2.2 Linear Optical Model

The LOM is optical sensitivity data derived from the optical model in the form of a matrix. Each degree of freedom in the optical model is perturbed and the change in system performance is recorded. The sensitivity is equal to the change in performance divided by the perturbation amount. A multidimensional matrix of sensitivity data is created by repeating this process for every degree of freedom for each optical element in the LUVOIR payload. For the LUVOIR payload, the LOM sensitivities are produced for the 6-DOF motion of each mirror including the primary mirror (PM), secondary mirror (SM), tertiary mirror (TM), Fast Steering Mirror (FSM), and Focal Plane Assembly (FPA). For the 6-DOF mirror motions or alignment errors, the change in wavefront and line of sight is recorded. The sensitivities in the LOM scale linearly with perturbation amount with this being a linear system. Simplifying the optical model this way is an efficient way to evaluate the impact of system disturbances such as jitter on the optical performance of the payload. The Matlab code used to generate the LUVOIR LOM has heritage use from the James Webb Space Telescope (JWST) LOM[2,3,4].

The LOM used for this analysis started using a monolithic primary mirror model with the primary mirror modelled as a rigid body. This simplification of the model allows for easy evaluation of the impact due to primary to secondary misalignment. To more accurately account for the segment motion contribution the primary mirror can be modeled as 120 individual hexagonal segments.

While the current method for creating a LOM could handle the primary mirror modelled as a rigid body, individually modeling the 120 segments proved to be challenging. With this challenge a dummy finite element model of the primary mirror optical surface was created. The LUVOIR A primary mirror consists of 120 segments with each segment being 1.2225m flat to flat in projection into the V2/V3 plane (regular hexagon).

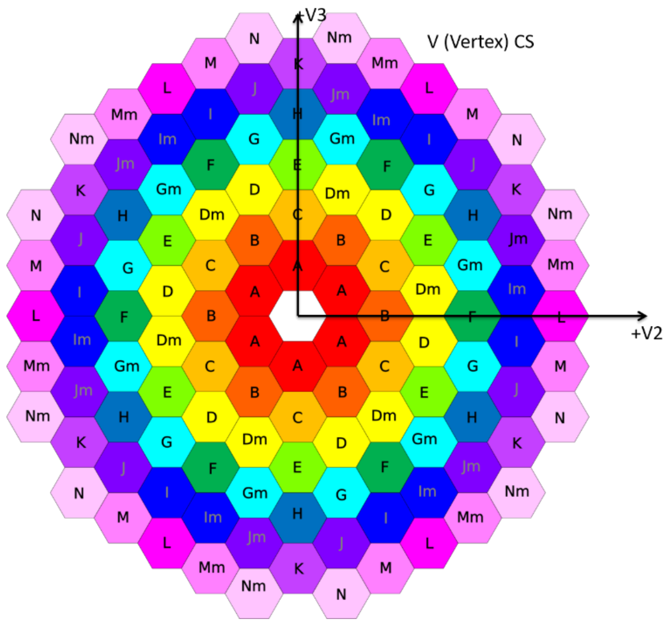

Figure 5: Primary mirror segment lettering projected on to the V2/V3 plane. This lettering system was used to provide the INT files needed to augment the monolithic LOM.

The segment gap is 6mm in projection into the V2/V3 plane. Each optical surface was independently moved in three rigid body translation and rotation degrees of freedom about the primary mirror V-Coordinate system. The displacements of the optical surface was fed into Sigmadyne's SigFit along with the primary mirror prescription to create 720 Code V interferogram files (.int or INT) for the optical path difference (OPD). The 720 INT files were then parsed to extract the sensitivity data needed to append the monolithic LOM already created. To align with the monolithic LOM already created the V2/V3 plane was transformed to have the segments projected onto a V1/V2 plane with the V3 along the optical axis.

When the segmented LOM was combined with the monolithic LOM for this analysis, only the translational DOFs for the LOM sensitivities have been able to be verified when compared to the monolithic LOM on its own. For this reason, only the translational DOF sensitivities will be used to create the results in this paper. Further work is needed to verify the rotational DOF sensitivities and fold into the analysis to create a complete set of results.

2.3 Fast Steering Mirror Disturbance Inputs

The FSM disturbance inputs were created from the FEM. The frequencies, damping, and mode shapes up to 200 Hz are imported to Matlab and frequency response functions (FRFs) give the amplitude of the response of displacement and rotation responses at the optical nodes for an input of 1N in the V1, V2, and V3 axes. A generic modal damping of 0.5% is included in the FRFs, but future analysis may reconsider this assumption.

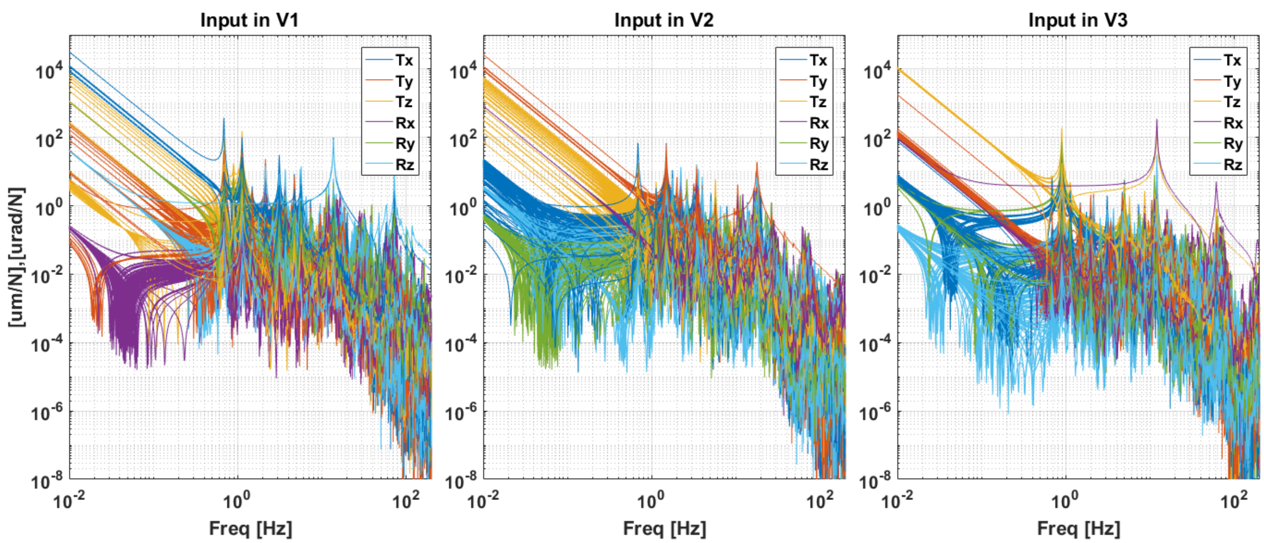

Figure 6: Displacement and rotation responses due to an input of 1N in the X, Y, and Z axes at frequencies up to 200Hz.

3. FSM DISTURBANCE RESULTS

3.1 Overall Results

The output of this analysis will give the wavefront error disturbance over frequencies up to 200Hz at the FSM input node. This output is one piece of the total wavefront error budget allocated to the LUVOIR payload. Other disturbance sources are combined together to give a total wavefront error for the optical path and this must be less than the requirement for mission success. Not included in this analysis is the translational and rotational segment control that is also baselined for the LUVOIR mission. Segment control would reduce the segment motion and therefore reduce the overall wavefront error from this disturbance. For simplicity in this case, just the input disturbance at the FSM node was analyzed.

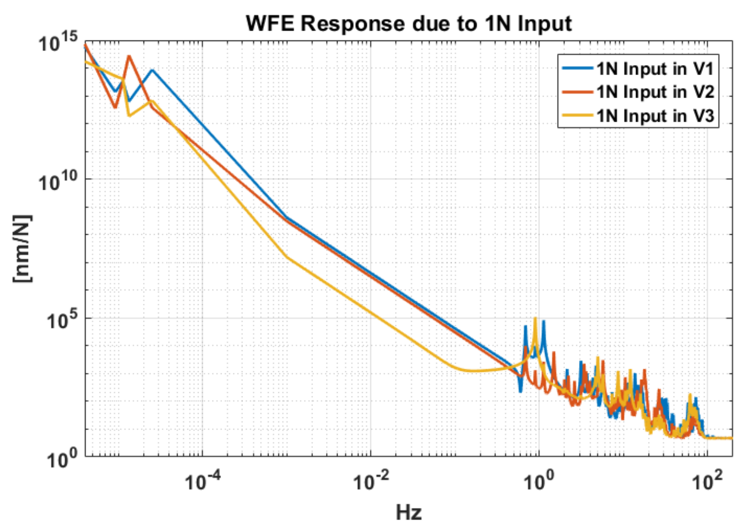

Figure 7: Over all frequencies up to 200Hz the wavefront error response due to a 1N input force at the FSM node in each axis.

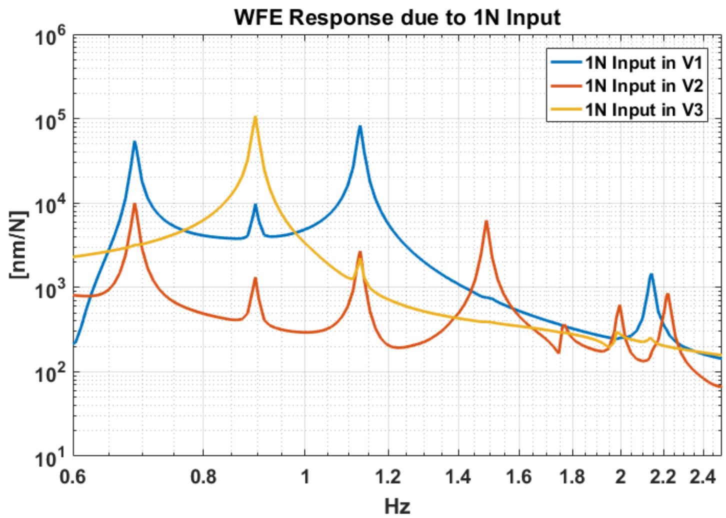

Figure 8: The first five modes between 0.5Hz and 2.0Hz are causing the largest disturbance to the optical performance.

3.2 Targeted Frequency Results

From Figure 8 there are a few frequencies with larger wavefront error due to the FSM disturbance input between 0.5Hz and 2.0Hz. Focusing in on these frequencies we can look at the LOM sensitivities and see how the optics are moving given an input disturbance at the FSM node at these specific frequencies.

The first frequency that causes a large disturbance in the V1 and V2 axes is at 0.69Hz. Figure 9 shows the WFE Output from a 1N input in V1, V2, and V3 axes at this frequency. The figures show the segment motion from the input disturbance dominates the WFE response. The response from the segment motion is three orders of magnitude larger than the primary mirror rigid body motion. From this we can focus on just the segment motion at the first few modes.

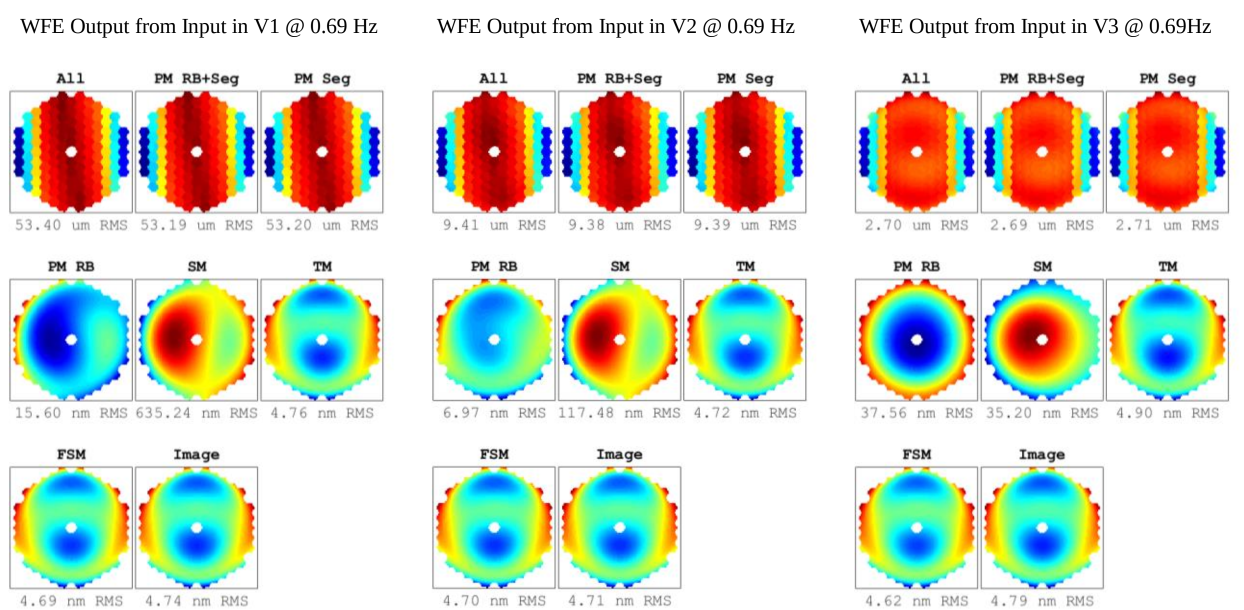

Figure 9: Specific optical outputs at the first disturbance frequency of 0.69Hz shown for all three input axes: V1, V2, V3.

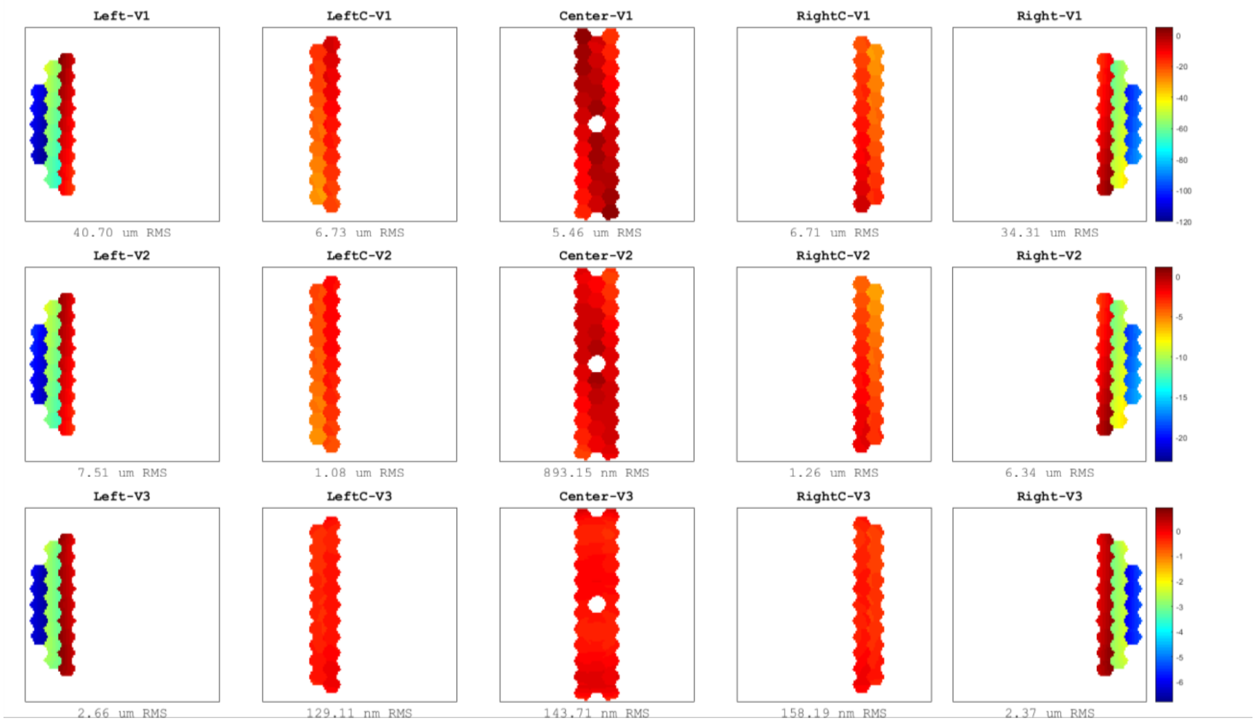

Figure 10: For each input axis, the segmented primary mirror is broken into slices to analyze further if parts of the primary mirror are disturbed more than others. The first row is the input in the V1 axis, second row is the V2 axis, and third row is the V3 input axis.

Now that the segment motion is shown to dominate the disturbance response, we can take a closer look at just the segment responses at the 0.69Hz frequency. The magnitudes are different between the three axes, but the direction of the response is similar between them. The further the slice is away from the center of the primary mirror, the larger the disturbance.

The results analogous to this first mode for the next four modes are shown in Table 1.

Table 1: Wavefront error due to 1N input disturbance at FSM node for largest five disturbance frequencies

Optical Section		**0.69Hz** V1, V2, V3[um]			**0.90Hz** V1, V2, V3[um]			**1.13Hz** V1, V2, V3[um]			**1.49Hz** V1, V2, V3[um]			**2.0Hz** V1, V2, V3[um]		
Total WFE		53	9.4	2.7	9.0	0.9	104	78	2.2	1.8	0.6	6.0	0.8	0.5	0.7	0.7
Segments		53	9.4	2.7	9.0	0.9	104	78	2.2	1.8	0.6	6.0	0.8	0.5	0.7	0.7
PM Slices	Left	41	7.5	2.6	10	1.4	116	96	3.0	2.9	0.7	7.3	0.4	0.2	0.7	0.3
	Left C	6.7	1.0	0.1	0.3	0.3	3.6	9.8	0.3	0.1	0.2	5.7	0.1	0.1	0.3	0.2
	Center	5.4	1.0	0.1	0.2	0.3	2.5	10	0.3	0.1	0.2	4.7	0.1	0.1	0.2	0.2
	Right C	6.7	1.3	0.2	0.4	0.3	4.5	9.4	0.4	0.2	0.3	5.4	0.1	0.1	0.4	0.2
	Right	34	6.3	2.4	9.2	1.2	102	105	3.4	3.1	0.9	5.9	0.4	0.3	0.6	0.3

4. CONCLUSIONS AND RECOMMENDATIONS FOR FSM SPECIFICATIONS

In order to meet the stringent requirements on the LUVOIR wavefront error mitigation of the FSM disturbance will be needed. Given the results shown in this paper and the assumption of a linear system if the FSM disturbance was limited the wavefront error due to segment motion would be less as shown in Figure 11.

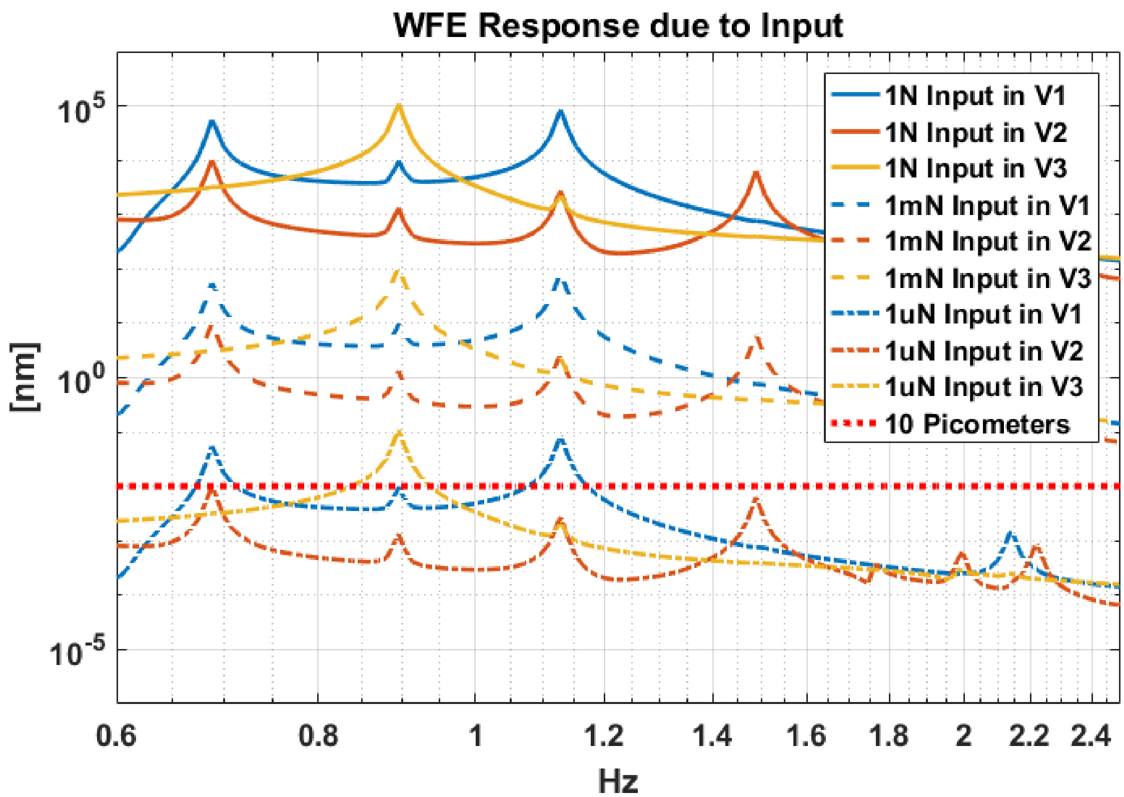

Figure 11: Assuming a linear system, reducing the input force would reduce the output response. This figure shows how reducing the input effects this output response of wavefront error using the original 1N input along with 1mN and 1uN.

A requirement for LUVOIR is to have the wavefront error stability less than 10 picometers RMS of the uncorrected system WFE per wavefront control step. Without any primary mirror segment control and only including the contribution of the FSM disturbances the results show the input disturbance must be less than 1 micro-Newton in all axes to achieve less than 10 picometers RMS wavefront error. Further analysis is needed to determine what exported forces can be achieved from a notional FSM, as well as how much the wavefront error stability will be reduced by the active segment metrology and control system that is not included in this analysis.

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