WFE Stability Budgeting for HWO

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Importance of Budgets (Static and Stability)

- Complete and accurate budgets are critical for mission design and success
  - In early stages, the budgets set performance requirements for systems, subsystems and components and are used to evaluate technology gaps.
  - Budgets can be adjusted to show impacts of choices at various levels (what's easy, what's hard?)
  - In later stages, the budgets track expected/achieved performance, uncertainties and margin to ensure the mission will meet its requirements, and thus its science goals
- Budgets can establish "common understanding" for large teams
  - Establishing allocations at various levels is useful in guiding development for architectures down through components
  - At this stage of HWO, we are speaking in ranges of allocations as there are still many architecture decisions to be made. This will be an iterative process between the roadmap groups and START/TAG/others.

Budgets are a critical tool in all phases of HWO – from early development through final verification

What is ULTRA and how does it connect to budgets?

- ULTRA ("Ultra-Stable Large Telescope Research and Analysis") is one of the two industry teams in NASA's Segmented Mirror Telescope Technology Program
  - Phase 1: ULTRA
    - A 1-year system level study to identify technology gaps and develop roadmaps
  - Phase 2: ULTRA-TM
    - A 4-year effort to mature key component technologies across the ultra-stable architecture

All phases of ULTRA are guided by system stability budgets to define performance regimes, evaluate candidate technologies, and identify gaps / areas for additional investment

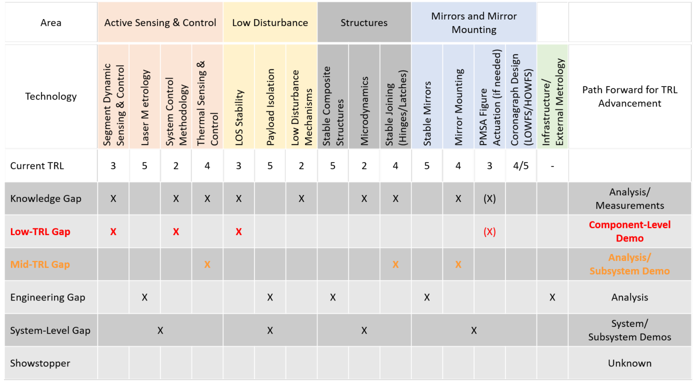
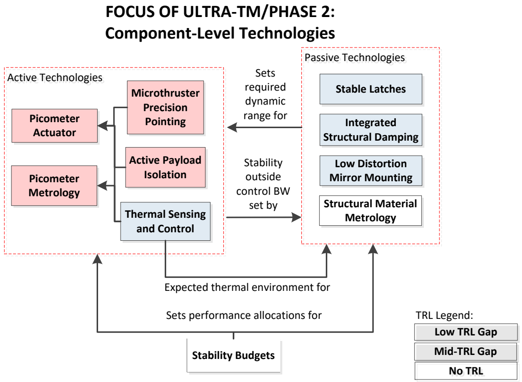


Image Credit: Ball, ULTRA Final Report 2019

Area	Active Sensing & Control				Low Disturbance			Structures			Mirrors and Mirror Mounting					
Technology	Segment Dynamic Sensing & Control	Laser Metrology	System Control Methodology	Thermal Sensing & Control	LOS Stability	Payload Isolation	Low Disturbance Mechanisms	Stable Composite Structures	Microdynamics	Stable Joining (Hinges/Latches)	Stable Mirrors	Mirror Mounting	PMSA Figure Actuation (if needed)	Coronagraph Design (LOWFS/HOWFS)	Infrastructure/ External Metrology	Path Forward for TRL Advancement
Current TRL	3	5	2	4	3	5	2	5	2	4	5	4	3	4/5	-	
Knowledge Gap	X		X	X	X		X		X	X		X	(X)			Analysis/ Measurements
Low-TRL Gap	**X**		**X**		**X**								(X)			**Component-Level Demo**
Mid-TRL Gap				**X**						**X**		**X**				**Analysis/ Subsystem Demo**
Engineering Gap		X				X		X			X				X	Analysis
System-Level Gap	X				X			X			X					System/ Subsystem Demos
Showstopper																Unknown



FOCUS OF ULTRA-TM/PHASE 2:
Component-Level Technologies

Active Technologies

Picometer Actuator

Picometer Metrology

Microthruster Precision Pointing

Active Payload Isolation

Thermal Sensing and Control

Sets required dynamic range for

Stability outside control BW set by

Passive Technologies

Stable Latches

Integrated Structural Damping

Low Distortion Mirror Mounting

Structural Material Metrology

Expected thermal environment for

Sets performance allocations for

Stability Budgets

TRL Legend:

Low TRL Gap

Mid-TRL Gap

No TRL

ULTRA Stability Budget Overview

- This presentation will cover the system stability budget
  - A static budget is also needed
- Developed for the LUVOIR A point design
- Focuses on the telescope
- Not going to cover details of coronagraph sensitivity modeling
- These are initial allocations and do not represent an optimized flight budget
- However, this is an example of an approach to budgeting for complex systems-of-systems

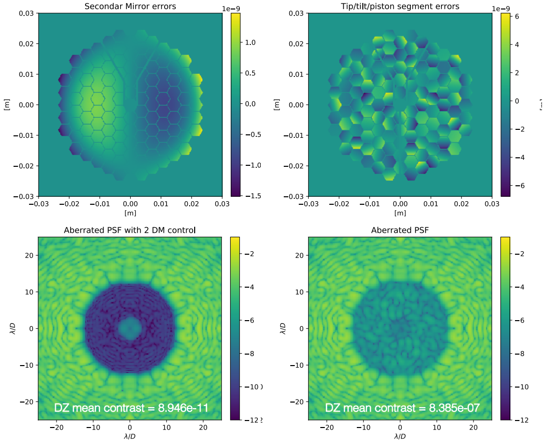
The Stability Budget is a living document

Mission architecture, coronagraph design, and passive and active controls will continue to evolve. But these values can provide a starting point to evaluate candidate approaches and technologies.

Key Assumptions

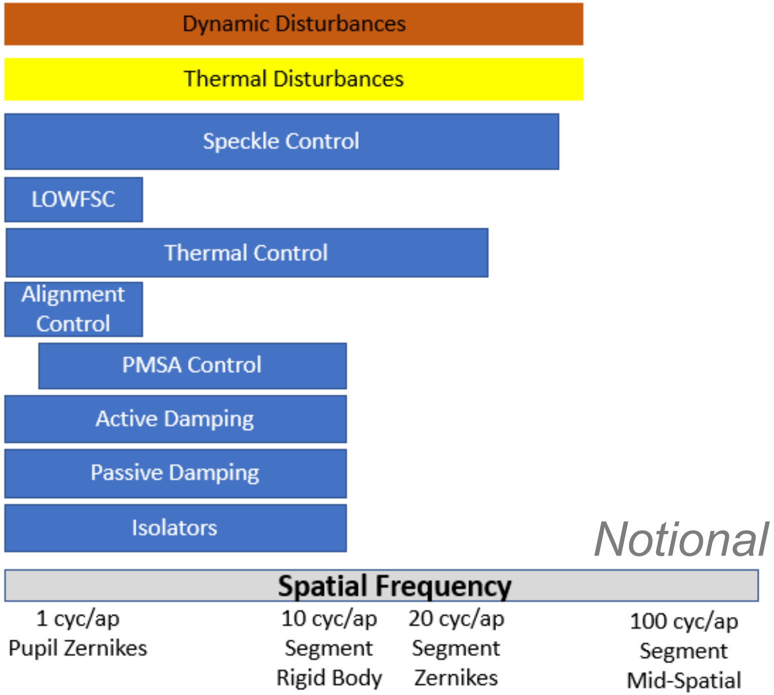
- The stability budget starts with contrast at the top level, then uses coronagraph sensitivity analysis to convert contrast to RMS WFE
  - RMS WFE flows down through the rest of the budget
  - STScI has done great work to look at tolerances per segment (Zernikes and optomech modes); this budget assumes a single tolerance applies to all segments, uses the worst-case optical sensitivity (RMS WFE / perturbation)
- Allocations combine in quadrature (reasonable assumption for complex systems)
  - PSD budgets may also be considered and may provide additional relaxation
- Does not include explicit margin/uncertainty allocations

Spatial Domains are set by Primary Mirror Segmentation



Juanola-Parramon et al. “Modeling Exoplanet Detection with the LUVOIR Telescope” (SPIE 2018)

Not all aberrations are created equal. Segment PTT has largest impact on contrast.



Dynamic Disturbances

Thermal Disturbances

Speckle Control

LOWFSC

Thermal Control

Alignment Control

PMSA Control

Active Damping

Passive Damping

Isolators

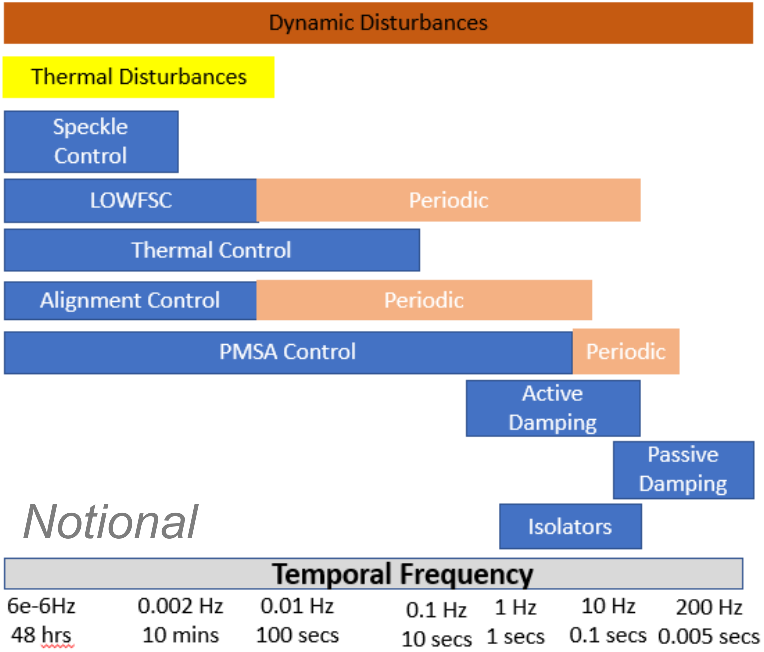
Notional

Spatial Frequency

1 cyc/ap Pupil Zernikes	10 cyc/ap Segment Rigid Body	20 cyc/ap Segment Zernikes	100 cyc/ap Segment Mid-Spatial

Image Credit: Ball, ULTRA Final Report 2019

Temporal Domains Set by Control Bandwidths



Dynamic Disturbances

Thermal Disturbances

Speckle Control

LOWFSC | Periodic

Thermal Control

Alignment Control | Periodic

PMSA Control | Periodic

Active Damping

Passive Damping

Isolators

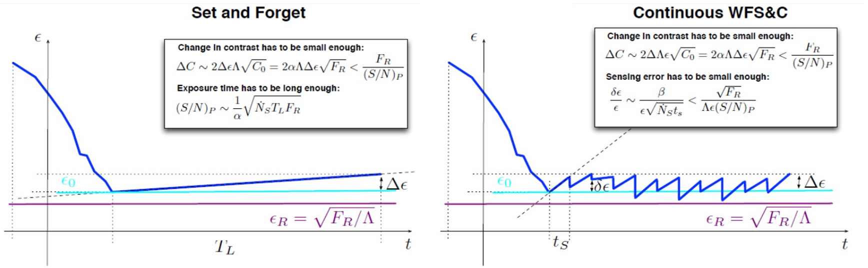
Notional

Temporal Frequency

6e-6Hz	0.002 Hz	0.01 Hz	0.1 Hz	1 Hz	10 Hz	200 Hz
48 hrs	10 mins	100 secs	10 secs	1 secs	0.1 secs	0.005 secs

Image Credits: Ball, ULTRA Final Report 2019

Image Credit: STScI, ULTRA Final Report 2019



Set and Forget

Change in contrast has to be small enough:

$$\Delta C \sim 2\Delta\epsilon\Lambda\sqrt{C_0} = 2\alpha\Lambda\Delta\epsilon\sqrt{F_R} < \frac{F_R}{(S/N)_P}$$

Exposure time has to be long enough:

$$(S/N)_P \sim \frac{1}{\alpha}\sqrt{\dot{N}_S T_L F_R}$$

Continuous WFS&C

Change in contrast has to be small enough:

$$\Delta C \sim 2\Delta\Lambda\epsilon\sqrt{C_0} = 2\alpha\Lambda\Delta\epsilon\sqrt{F_R} < \frac{F_R}{(S/N)_P}$$

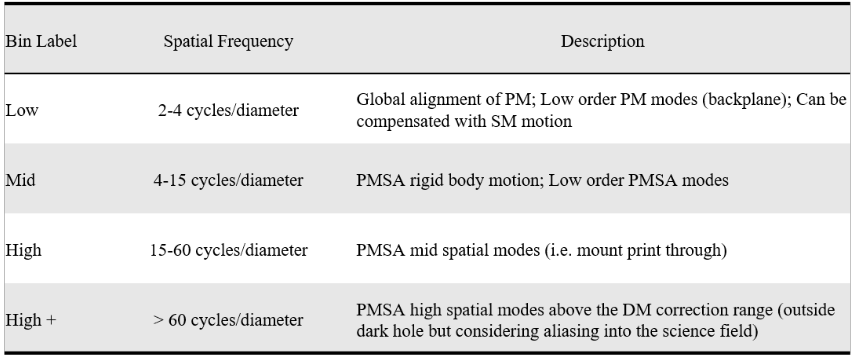
Sensing error has to be small enough:

$$\frac{\delta\epsilon}{\epsilon} \sim \frac{\beta}{\epsilon\sqrt{\dot{N}_S t_s}} < \frac{\sqrt{F_R}}{\Lambda\epsilon(S/N)_P}$$

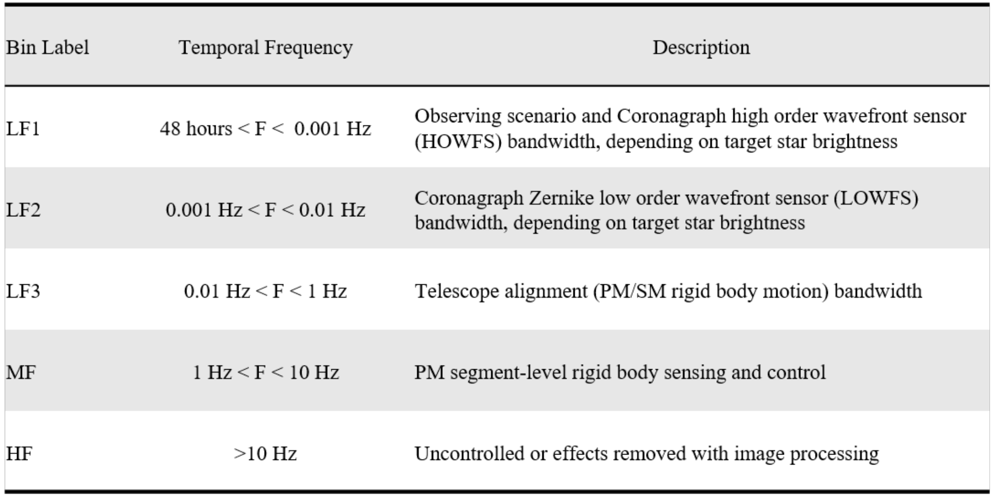
Time evolution of wavefront error for “Set and Forget” (left) and “Continuous WFSC” (right) observing scenarios.

The total allowable drift is the same, but the drift rate of change is a function of the time constant for each scenario.

Definition of Spatial and Temporal Domains



Bin Label	Spatial Frequency	Description
Low	2-4 cycles/diameter	Global alignment of PM; Low order PM modes (backplane); Can be compensated with SM motion
Mid	4-15 cycles/diameter	PMSA rigid body motion; Low order PMSA modes
High	15-60 cycles/diameter	PMSA mid spatial modes (i.e. mount print through)
High +	> 60 cycles/diameter	PMSA high spatial modes above the DM correction range (outside dark hole but considering aliasing into the science field)

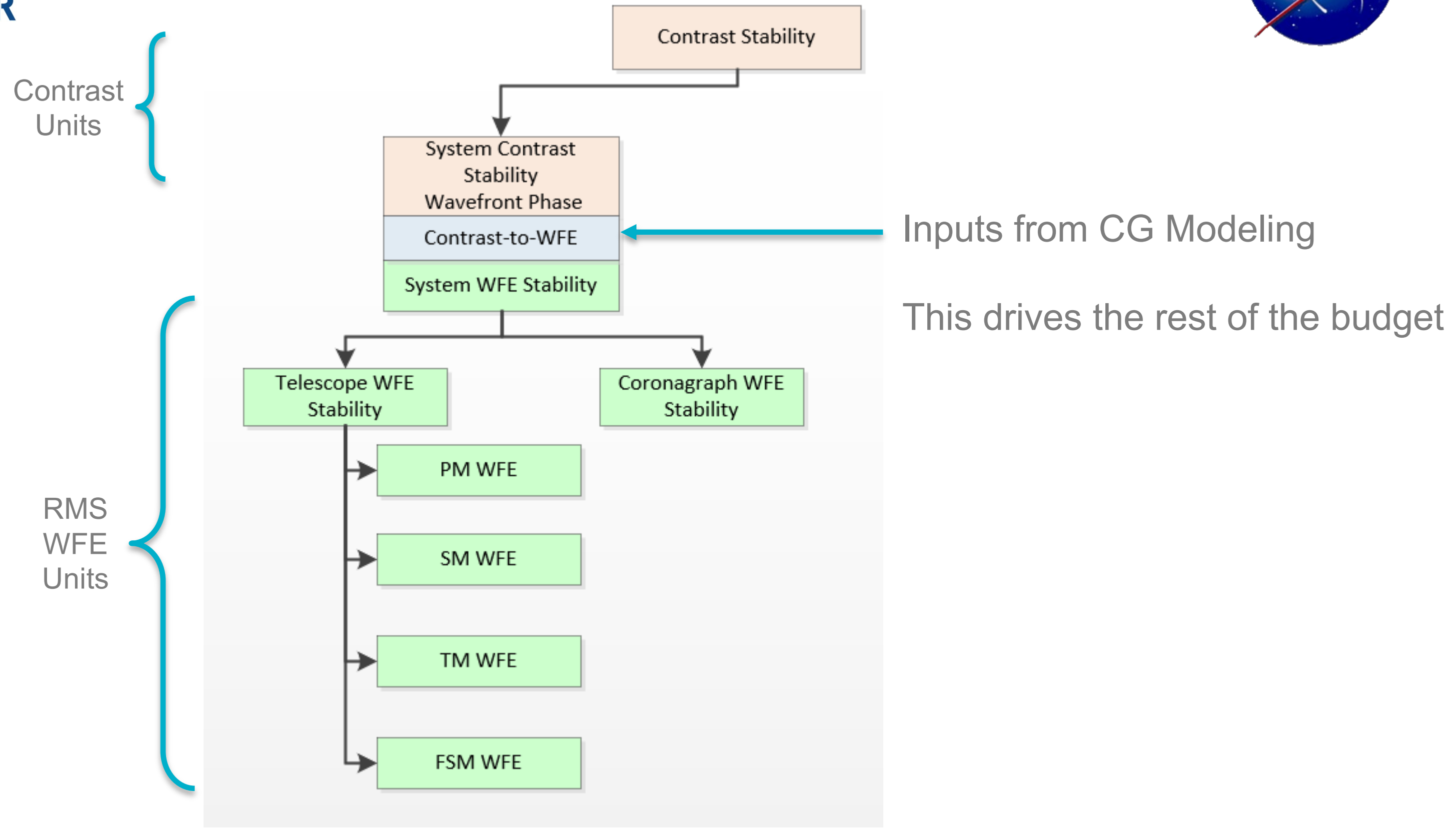


Bin Label	Temporal Frequency	Description
LF1	48 hours < F < 0.001 Hz	Observing scenario and Coronagraph high order wavefront sensor (HOWFS) bandwidth, depending on target star brightness
LF2	0.001 Hz < F < 0.01 Hz	Coronagraph Zernike low order wavefront sensor (LOWFS) bandwidth, depending on target star brightness
LF3	0.01 Hz < F < 1 Hz	Telescope alignment (PM/SM rigid body motion) bandwidth
MF	1 Hz < F < 10 Hz	PM segment-level rigid body sensing and control
HF	>10 Hz	Uncontrolled or effects removed with image processing

These notional bins are based on the LUVOIR active sensing and control basleine architecture.

Image Credits: Ball/STScI, ULTRA Final Report 2019

Stability Budget Structure



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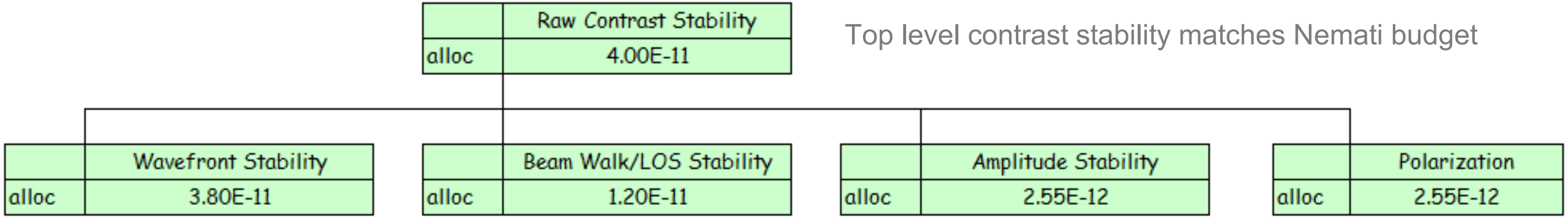
Top Level Contrast Stability



Top level contrast stability matches Nemati budget

Focus of this budget

Assessed beam walk WFE for allowable PM/SM misalignments from WFE budget (~1e-11)

Assessed 0.3 mas LOS WFE in each axis (LF3/MF/HF ~3e-12)

Allocated, but not yet assessed

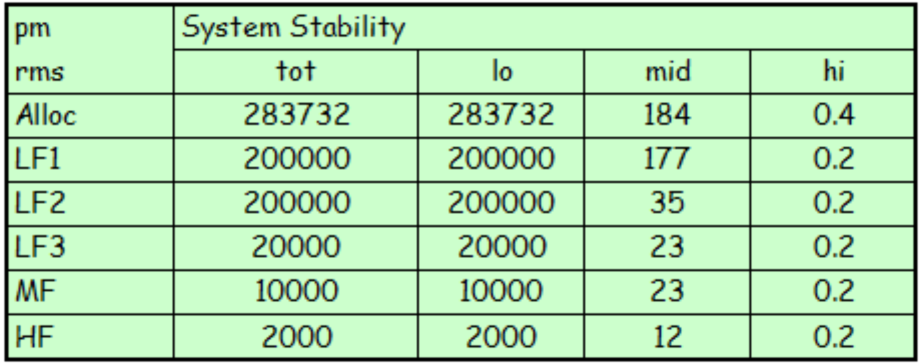
The contrast stability is set by the mission science goals

Allocations are made to all expected phenomena, but not all have been assessed

Use Coronagraph Sensitivities to create WFE allocations vs. Spatial, Temporal Frequency

- Sensitivities generated by STScI for LUVOIR A APLC
  - Mv = 5 host star
  - No detector noise
  - Includes Continuous WFSC in the coronagraph (assumes it runs as fast as it can given photon noise limits – will probably run slower in practice)
  - Hi modes use correlated sine wave errors – may be too conservative. Looking at this currently in ULTRA-TM

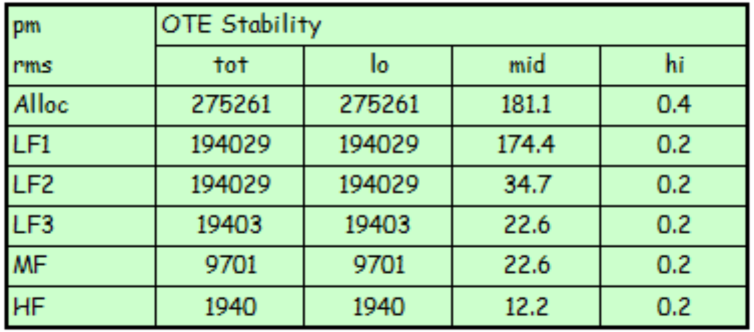
These all combine to 3.8e-11 change in contrast



pm	System Stability			
rms	tot	lo	mid	hi
Alloc	283732	283732	184	0.4
LF1	200000	200000	177	0.2
LF2	200000	200000	35	0.2
LF3	20000	20000	23	0.2
MF	10000	10000	23	0.2
HF	2000	2000	12	0.2

Requirements loosen significantly at slower frequencies due to CG-based continuous WFSC
(need to also consider dynamic range, linearity, etc. of the coronagraph-based controls)

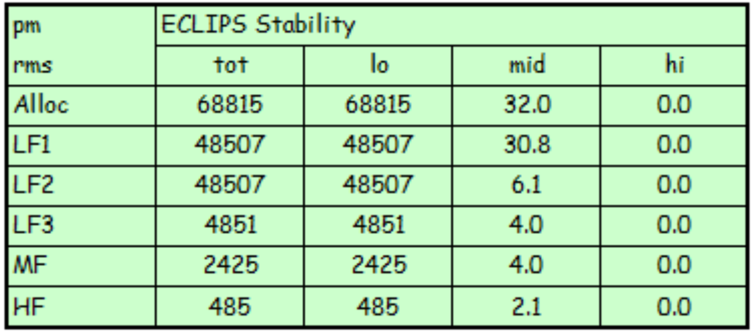
Allocate to SI, OTE



pm	OTE Stability			
rms	tot	lo	mid	hi
Alloc	275261	275261	181.1	0.4
LF1	194029	194029	174.4	0.2
LF2	194029	194029	34.7	0.2
LF3	19403	19403	22.6	0.2
MF	9701	9701	22.6	0.2
HF	1940	1940	12.2	0.2

Focus of this budget

Allocate to PM, SM, TM, FSM



pm	ECLIPS Stability			
rms	tot	lo	mid	hi
Alloc	68815	68815	32.0	0.0
LF1	48507	48507	30.8	0.0
LF2	48507	48507	6.1	0.0
LF3	4851	4851	4.0	0.0
MF	2425	2425	4.0	0.0
HF	485	485	2.1	0.0

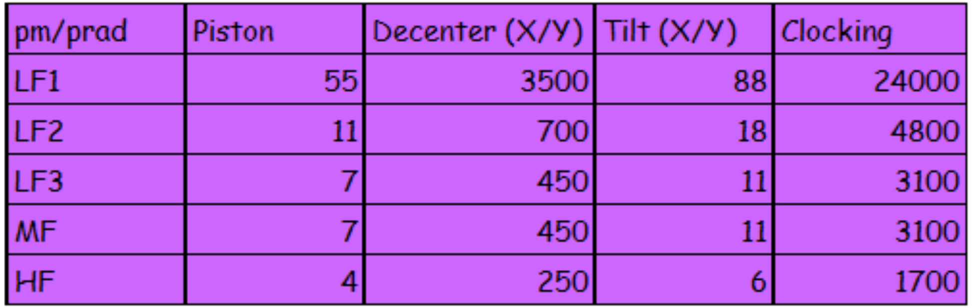
Allocated, but not yet assessed

Lo – thermal stability
Mid – DM stability

Can rebalance as design matures

Ex. PMSA Rigid Body

- Take a sub-allocation of PM MID WFE and use segment optical sensitivity to calculate the allowable “post-control” pose residual



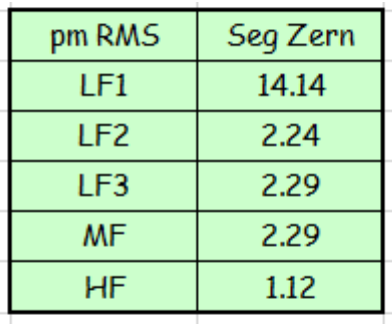
pm/prad	Piston	Decenter (X/Y)	Tilt (X/Y)	Clocking
LF1	55	3500	88	24000
LF2	11	700	18	4800
LF3	7	450	11	3100
MF	7	450	11	3100
HF	4	250	6	1700

Input to components like ZWFS, edge sensors, laser metrology, actuators

Residuals set performance levels on passive/active control
If active control is used, the “pre-control” passive stability is relaxed

Ex. PMSA Low Order Deformation (Power, Astig)

- Take a sub-allocation of PM MID WFE and allocate to PMSA low order zernikes / deformations



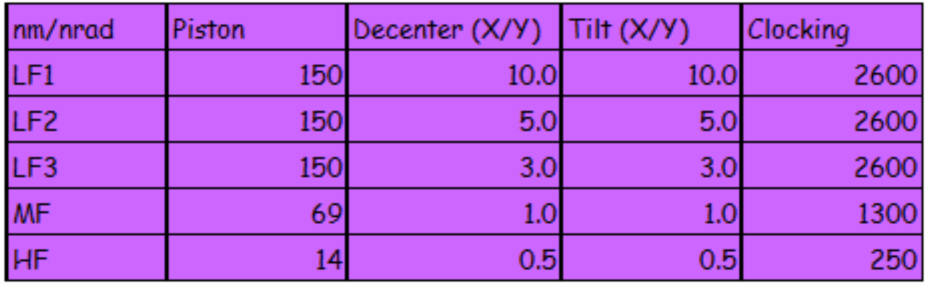
pm RMS	Seg Zern
LF1	14.14
LF2	2.24
LF3	2.29
MF	2.29
HF	1.12

Input to mirror substrate design, mounting, thermal control, dynamic disturbances

Consider not only WFE but also how segment distortion affects the rest of the WFSC architecture

Ex. SM Rigid Body

- Take a sub-allocation of SM LO WFE and use optical sensitivity to calculate the allowable “post-control” pose residual



nm/nrad	Piston	Decenter (X/Y)	Tilt (X/Y)	Clocking
LF1	150	10.0	10.0	2600
LF2	150	5.0	5.0	2600
LF3	150	3.0	3.0	2600
MF	69	1.0	1.0	1300
HF	14	0.5	0.5	250

Input to SMSS passive and active stability, laser metrology and actuators

Residuals set performance levels on passive/active control.
If active control is used, the “pre control” passive stability is relaxed

Summary

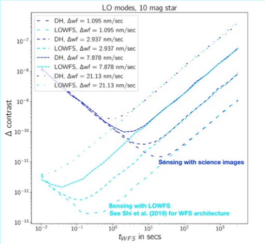
- The ULTRA stability budget contains initial allocations for the LUVOIR A Point Design
- The budget is a function of spatial and temporal frequency
- The budget relies on coronagraph sensitivity analysis in those regimes to meet the desired contrast
- The allocations from this presentation represent a starting point to assess various approaches and technologies to create an ultra-stable architecture. They should not be considered requirements and allocations may change significant depending on how the architecture matures.

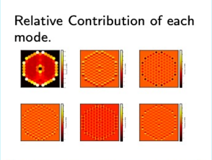
ULTRA-TM Objective:

Parallel maturation of key component technologies across the ultra-stable architecture

CORONAGRAPH SENSITIVITES

Calculate contrast stability vs. spatial-temporal domain, active WFSC in coronagraph, noise



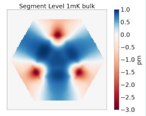

Relative Contribution of each mode.

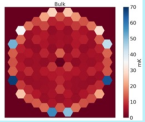
MID modes requirements with MIDWFS

Mag 0 star, < 15 pm/sec, $t_{WFS} > 0.5$ sec.

Mag 5 star, < 2 pm/sec, $t_{WFS} > 20$ sec.

Mag 10 star, < 0.5 pm/sec, $t_{WFS} > 2000$ sec.

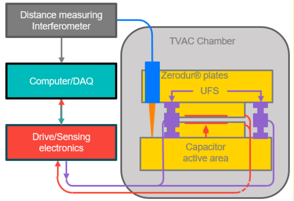




Key Result: Derived allocations for system stability budget, set necessary performance for systems/ subsystems/components, used to evaluate technology gaps

SEGMENT SENSING AND CONTROL

Demonstrate picometer-level edge sensor and actuator components with flight-traceable designs. Model network performance.


Distance measuring Interferometer

Computer/DAQ

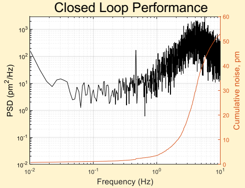
Drive/Sensing electronics

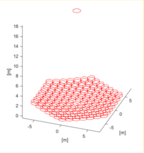
TVAC Chamber

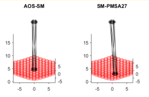
Zerodur® plates

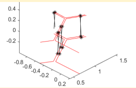
UFS

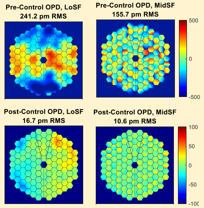
Capacitor active area







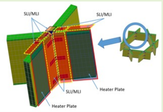


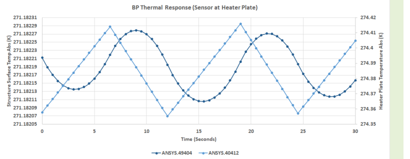


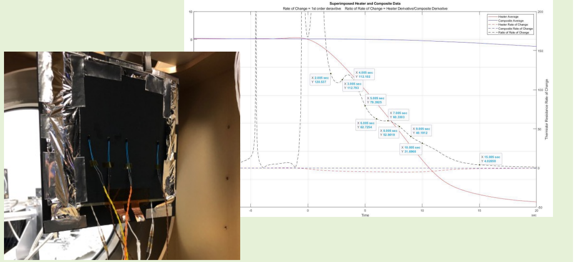
Key Result: Achieved 2.5 pm RMS closed loop sense/actuate residual from 0.01-10 Hz. Developed flexible time domain simulation for architecture trades and component evaluation

THERMAL SENSING AND CONTROL

Develop a radiative heating approach with stability in the mK regime







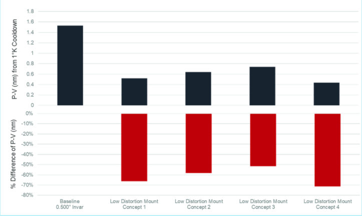
Key Result: Modeling and hardware demo of sub-mK thermal stability from rigid heater-integral-to-composite heater panel on structure element. Identified novel temp sensors.

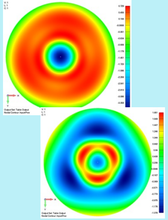
ULTRA-TM Objective:

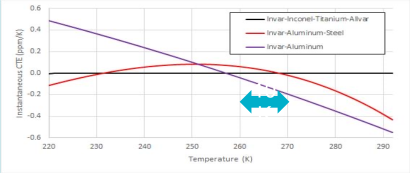
Parallel maturation of key component technologies across the ultra-stable architecture

STABLE MIRROR MOUNTING

Design of novel mount pads, struts with improved passive stability to reduce mirror distortion



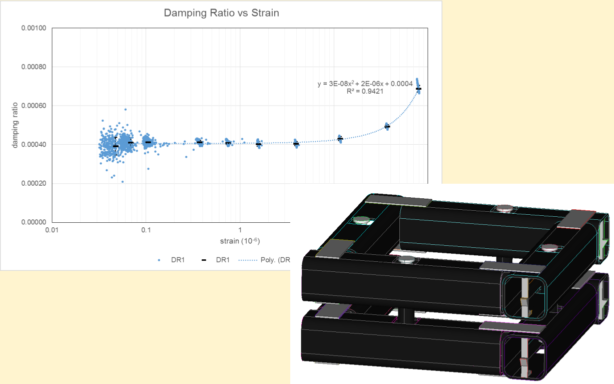




Key Result: Design and hardware demo of novel pad geometry with predicted 15-20X reduction in SFE distortion over solid pad. Developed strut design with metal alloys that has comparable CTE to ULE/Zerodur.

STABLE STRUTURES – LATCHING AND DAMPING

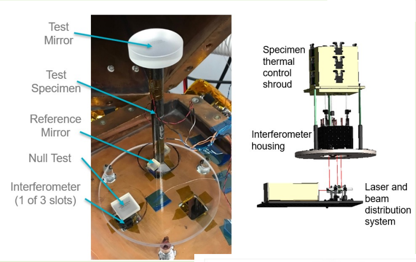
Increase damping in large structures with foil treatment. Re-design latches to improve passive thermal & dynamic stability.

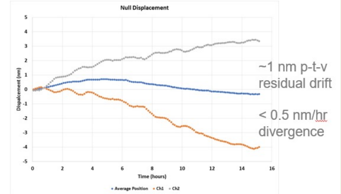


Key Result: Hardware demo showed foil appreciably increased damping ratio in composite coupons. Hardware demo of latchplane test article showed new design reduces deformation by several orders of magnitude.

MATERIAL PROPERTY METROLOGY

Reduce uncertainty in measured CTE/CME of composites by 100X





Key Result: 10X improvement in displacement measurement. Improved isolation from lab environment. Completed analysis of alignment stability on displacement.