Ultra-Stable Large Telescope Research and Analysis (ULTRA): Progress to Date

Mirror Tech Days
Nov 7, 2018

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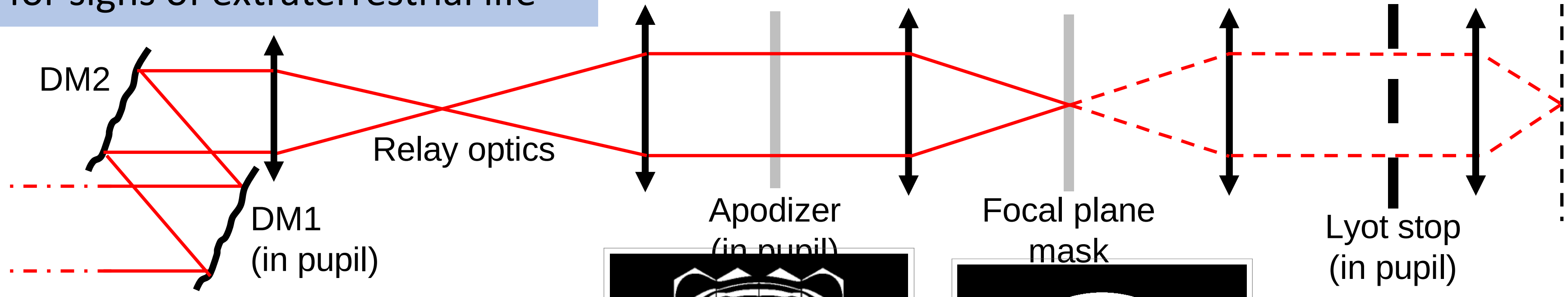
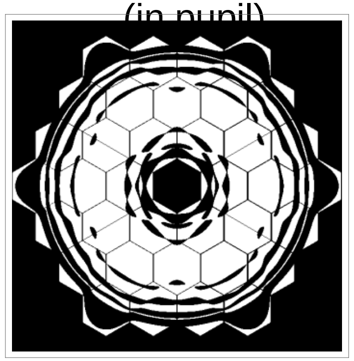
This work is supported by NASA ROSES Grant: 80NSSC18K0820

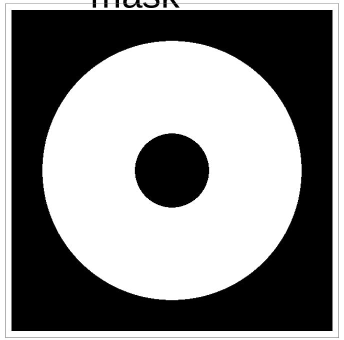
Study is in-process so all data is preliminary

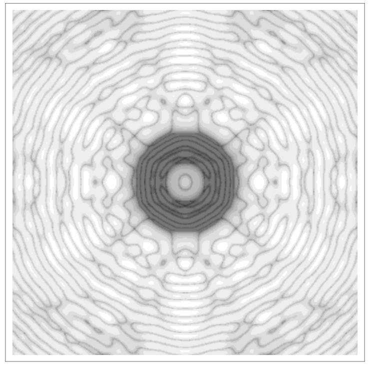
Finding Exo-Earths

Want to find Earth–like Planets and Characterize the Atmosphere for signs of extraterrestrial life







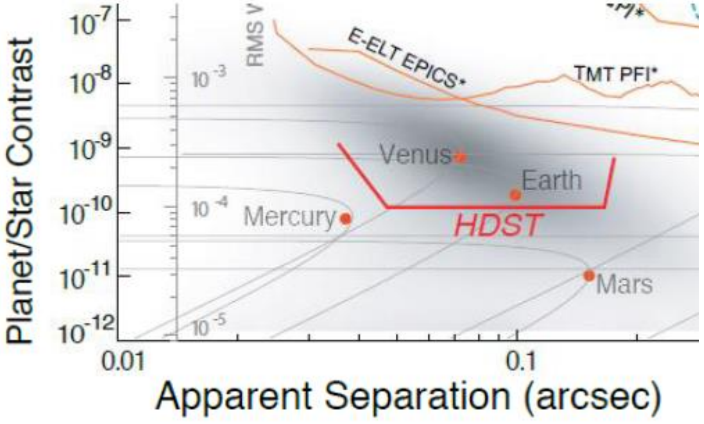


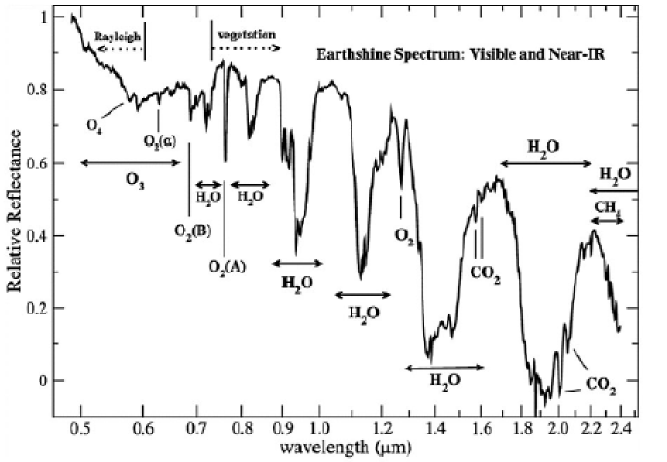
<u>Basic Coronagraph Operation</u>

1. Pupil and Focal Plane Masks block Starlight at small angular separation from star

2. Deformable Mirrors control Amplitude and Phase to produce a High Contrast region in image plane

3. System must maintain optical stability between DM control updates





Shaklan et al. "Segmented Coronagraph Design and Analysis", High Contrast Imaging Workshop, Nov 14,2016

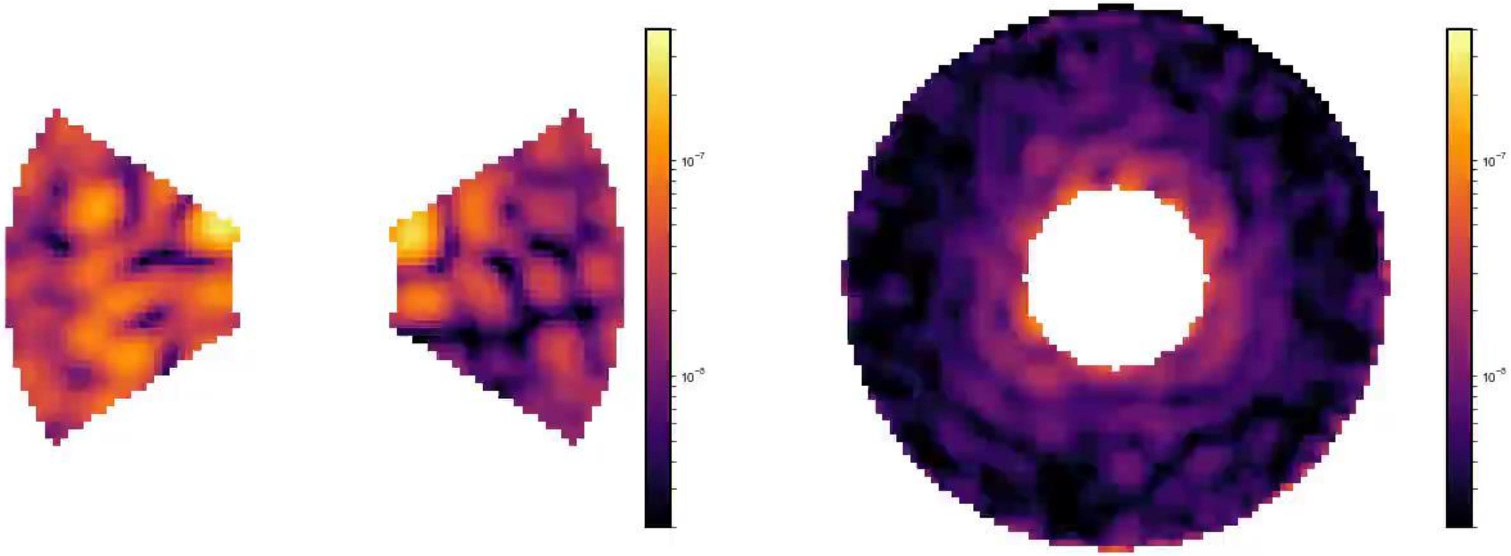
Study for ultra –stable segmented telescopes

Exoplanet Telescope Stability
"10 picometers/10 mins"
-Phil Stahl – Poet and Telescope Designer

System stability is driven by the available stellar photons to do speckle sensing and control at the science detector

Research Goal

- Establish the large, segmented telescope stability needs to support the direct imaging of exoplanets Science Missions
- System Study to establish the optical stability Technology Gaps and produce Technology Development Roadmap



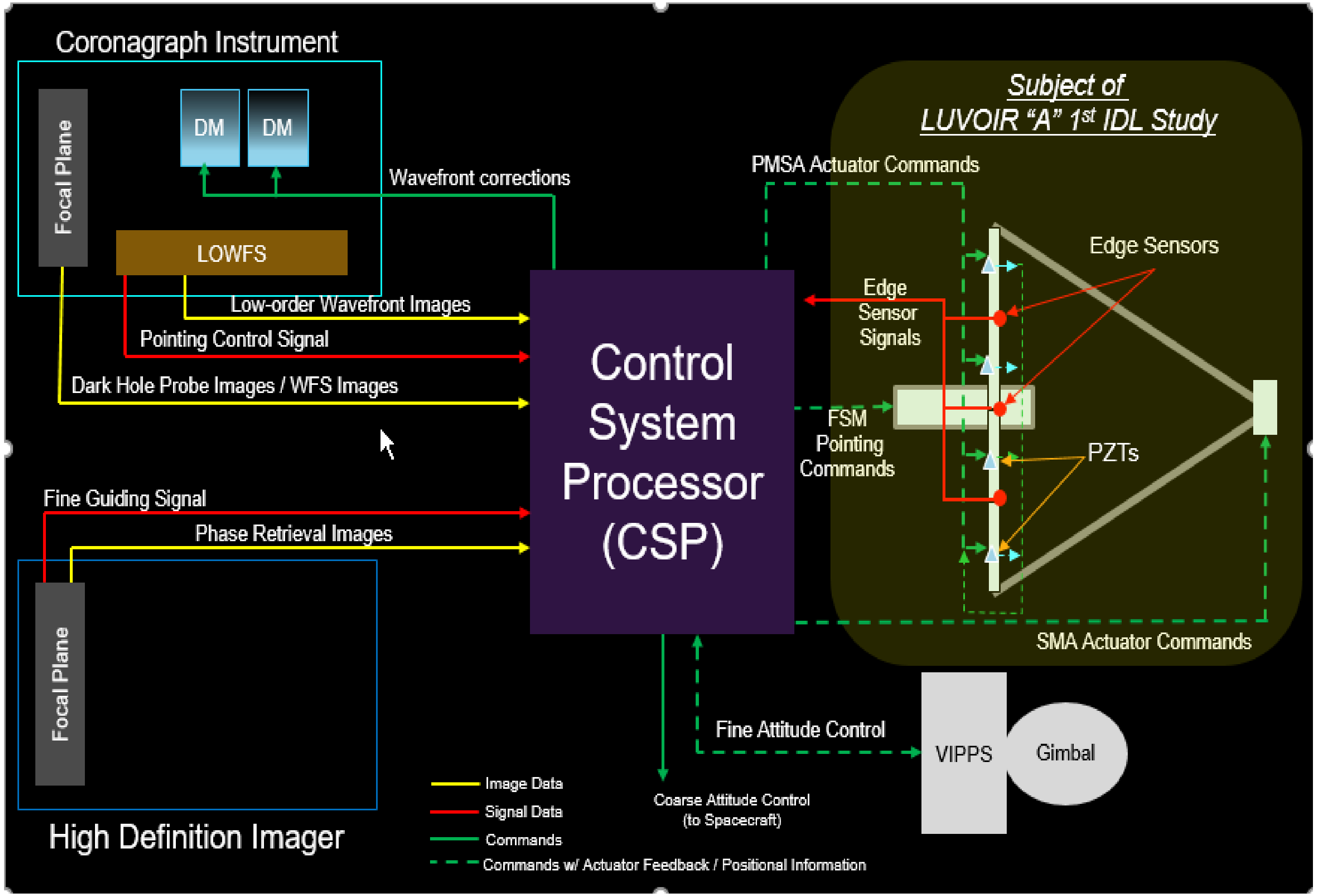
Most of the previous work on stability looked at the spatial frequency needs for segmented telescopes.
This work focuses on the temporal domain including the need for and capabilities of active control systems

Segmented Telescope Control System Architecture Concept

High Order Wavefront Sensor- Speckle Control

Low Order Wavefront Sensor- Wavefront Control

Fine Guiding Sensor- Line of Sight Control



Edge Sensors- Segment to Segment Control

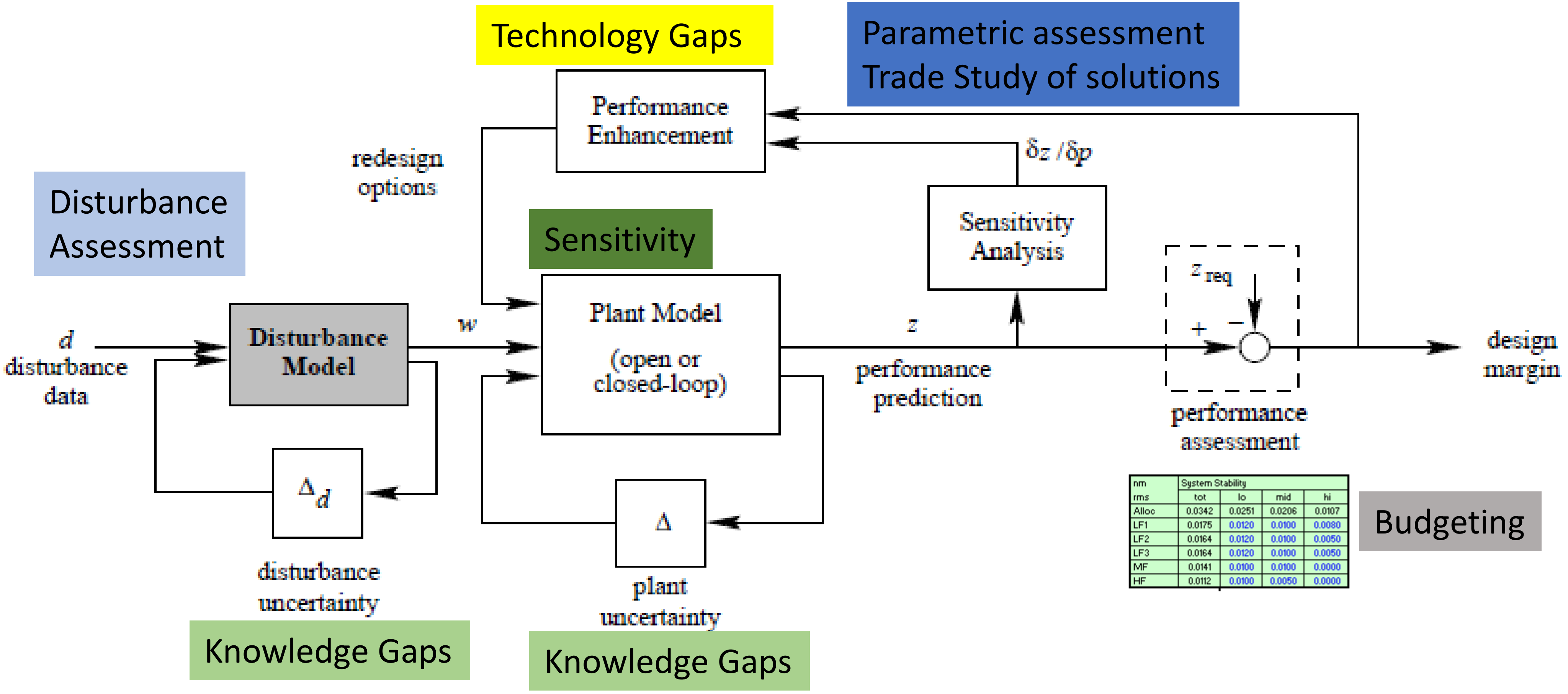
Laser Alignment Sensors Telescope Optics Control

Thermal Sensing and Control

VIPPS – Vibration Isolation and Pointing Control

Lee Feinberg; Matthew Bolcar; Scott Knight; David Redding," Ultra-stable segmented telescope sensing and control architecture", SPIE (2017)

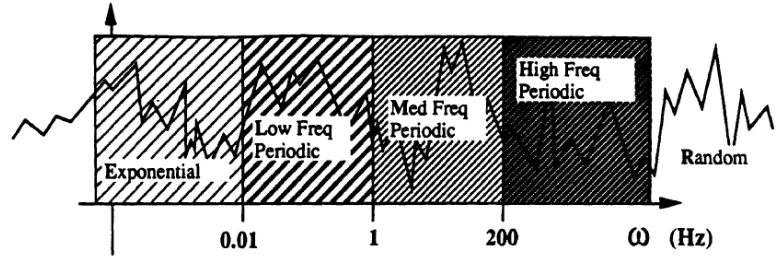
Technology Evaluation Process



nm rms	System Stability tot	lo	mid	hi
Alloc	0.0342	0.0251	0.0206	0.0107
LF1	0.0175	0.0120	0.0100	0.0080
LF2	0.0164	0.0120	0.0100	0.0050
LF3	0.0164	0.0120	0.0100	0.0050
MF	0.0141	0.0100	0.0100	0.0000
HF	0.0112	0.0100	0.0050	0.0000

- Plant model is either Sensitivity analysis or Numerical Model
  - Open or closed loop defines the performance needs/limitations of the controller

Classical Disturbances



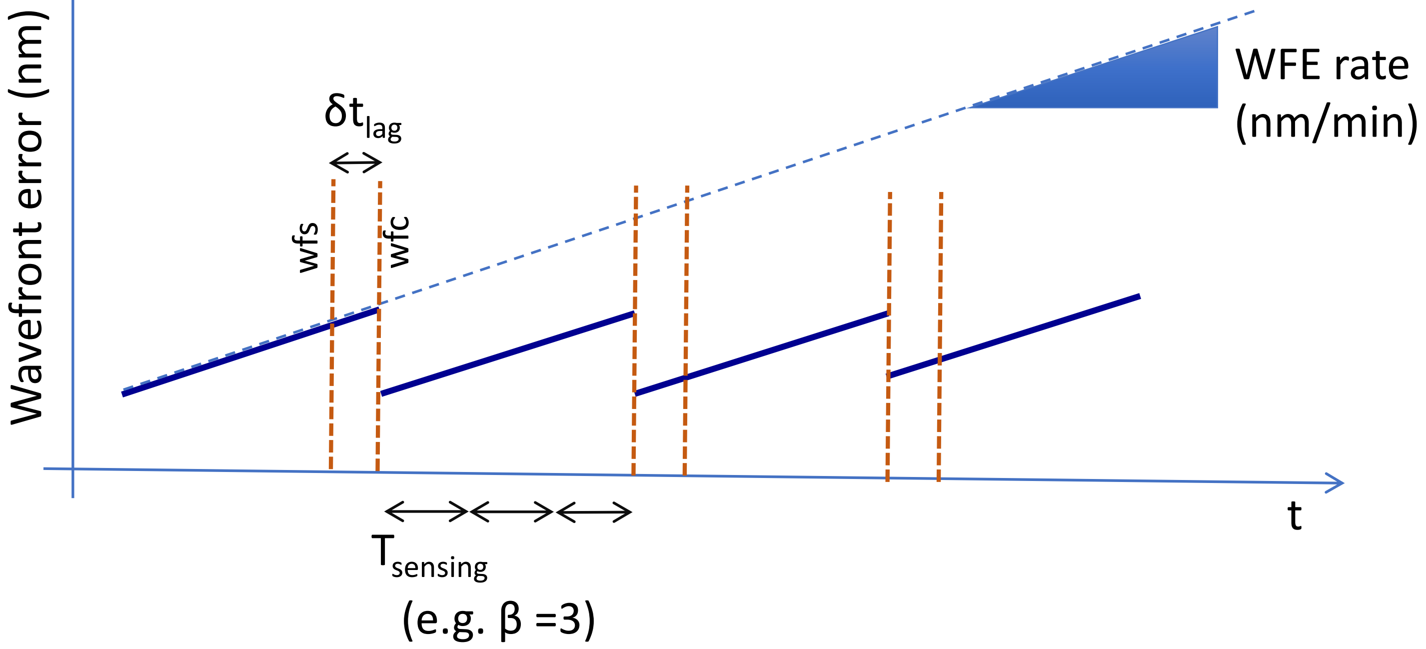
	Freq Range	Source
Exponential	10^{-6} -> 10^{-2} Hz	Environmental, Thermo-elastic
Low Freq Periodic	10^{-2} -> 1 hz	Flexi-body interaction torques (damping), and momentum exchange with flexible appendages and movable elements; vehicle fundamental modes, Internal thermal-mechanical fluctuations: active cycling of electric heaters; cyclic operation of dissipating devices, Fluid slosh: propellant, cryogenics; Low frequency electromechanical
Mid Freq Periodic	1 -200 Hz	Electromechanical devices: RWA/CMG's, data recording devices, servomechanisms,pumps, displacement actuators, active mounts 'Stiffer' flexi-body interactions; Higher harmonics of fluid slosh
High Freq Periodic	200+ Hz	Higher harmonics of electromechanical devices; Electrical noise: AC current
Random, Impulsive	DC- 200+Hz	Fluid turbulence, Friction, Sensor / electrical noise (photon, thermal, shot) Micrometeoroid impact: very low freq Non-periodic gimballing (thrusters, sensors, antennae): low freq Thruster firing - transients: low-high freq

This effort is especially interested in non-traditional sources that may be important at picometers

Science Observations trade spaces identified

Low Order and High Order Wavefront Sensing

Timescales: fundamental limits vs practical constraints.



Total sensing time follows a fundamental property: $T_{sensing}$ x N_{phot} x Contrast >1

WF estimate

$$\hat{\varepsilon} = \varepsilon_0 + \delta\varepsilon$$

WF residual after correction

$$\hat{\varepsilon} - \varepsilon_{DM} = \varepsilon_{residual}$$

DM command

$$\varepsilon_{DM} = \hat{\varepsilon} + (1-\gamma)\ \eta_{rate}\ \Delta t_{lag}$$

Estimation error

$$\delta\varepsilon = \zeta\ \delta\varepsilon_{phot}$$

Estimation error

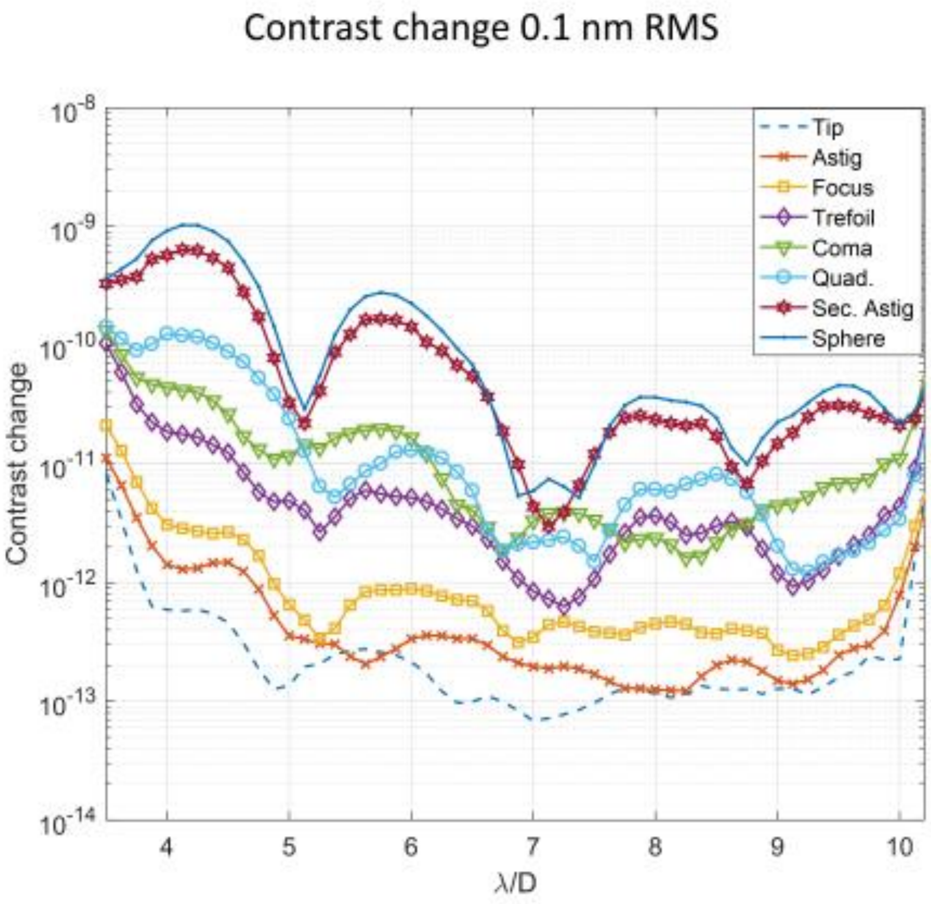
$$\delta\varepsilon_{phot} = \beta\lambda/2\pi\ \sqrt{(T_{sensing}\ N_{phot})}$$

β: wavefront sensor efficiency

γ: Predictive control efficiency

ζ: Predictive sensing noise efficiency

Work in progress



- Low-spatial frequencies (Zernike modes), easiest, most understood case.
- Coronagraphs are designed to be robust to these modes.
- 100 pm rms yields contrasts ~10^-10 or below all the way to spherical

Segment Errors		Global Errors	
Mode	pm	Mode	pm
Segment Piston	7	Global Bend about Y	209
Segment Tilt	13	Global Bend about X	224
Segment Power	23	Global Spherical	624
Segment Astigmatism	32	Global Hexafoil	778
Segment Trefoil	87	Global Zernike Coma	1049
Segment Hexafoil	314	Global Trefoil	2322
		Global Seidel Coma	2872
		Global Power	5798

Segment-level aberrations are the most demanding and drive the "10 pm " need

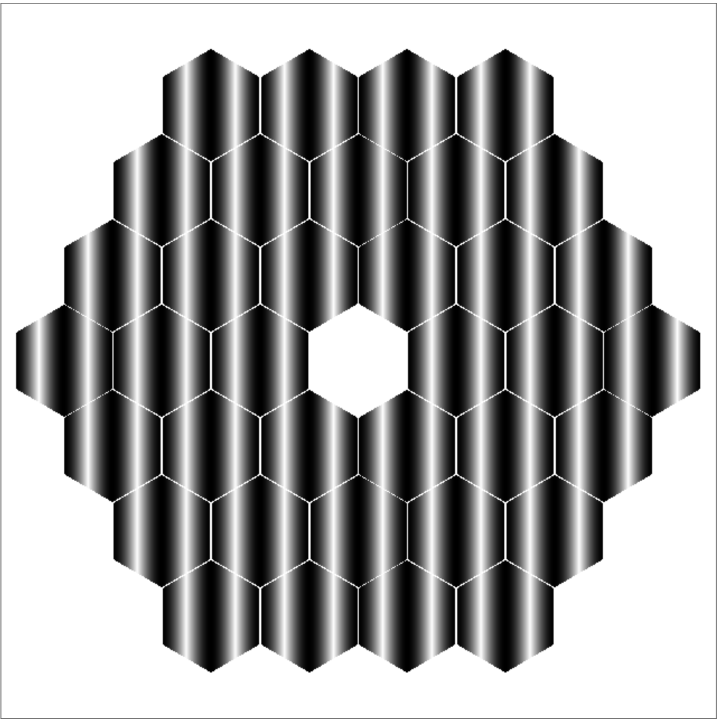
Nemati at al. , "Effects of space telescope primary mirror segment errors on coronagraph instrument performance", (SPIE 2017)

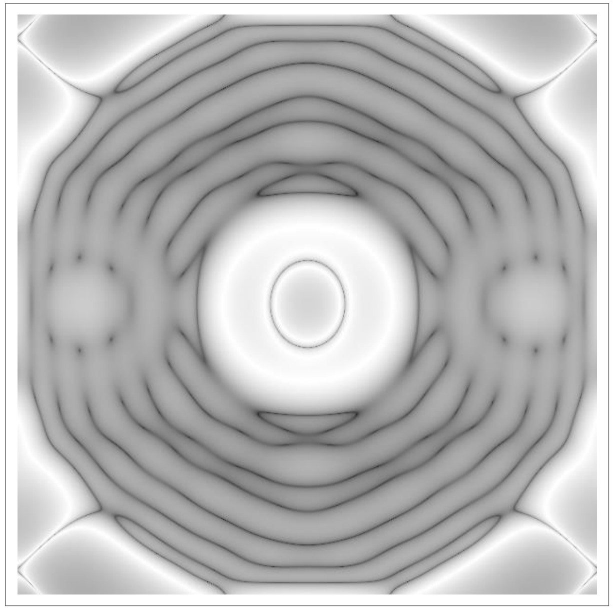
Budgets are developed based on Contrast Stability

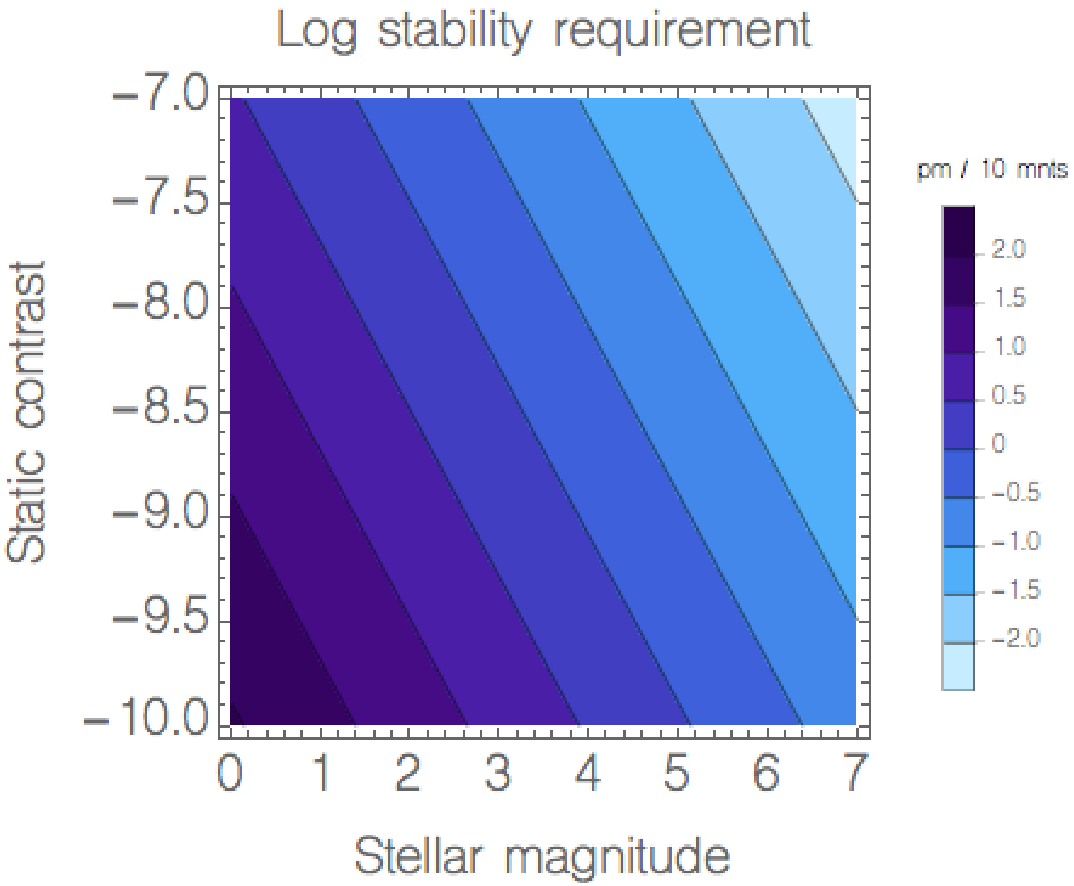
HI spatial scales

Contrast target: 10^-10

- 1. Sensitivities: 1 pm maps to 10^10



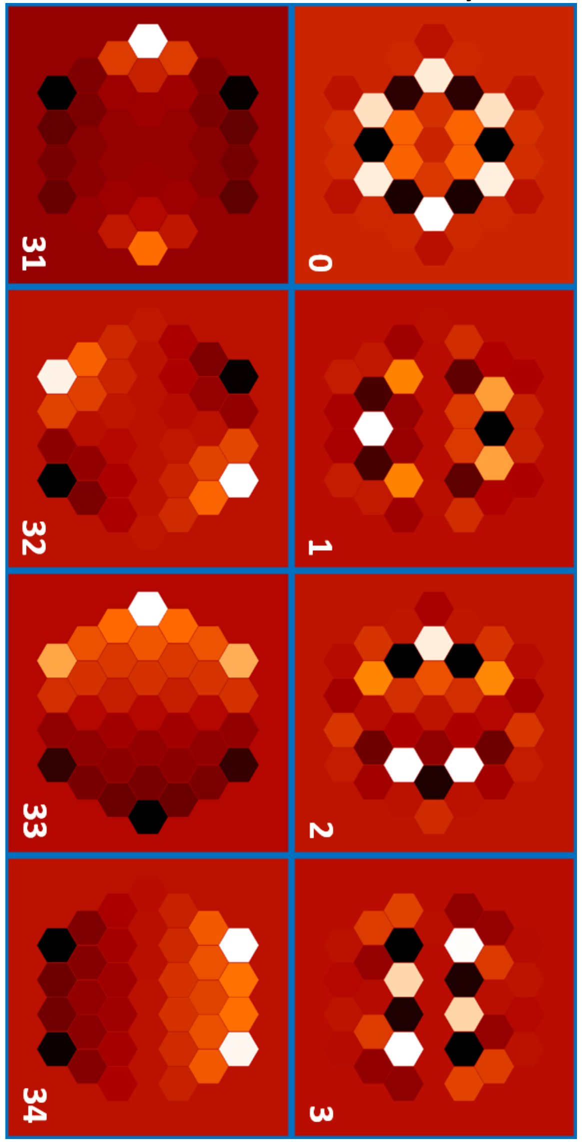




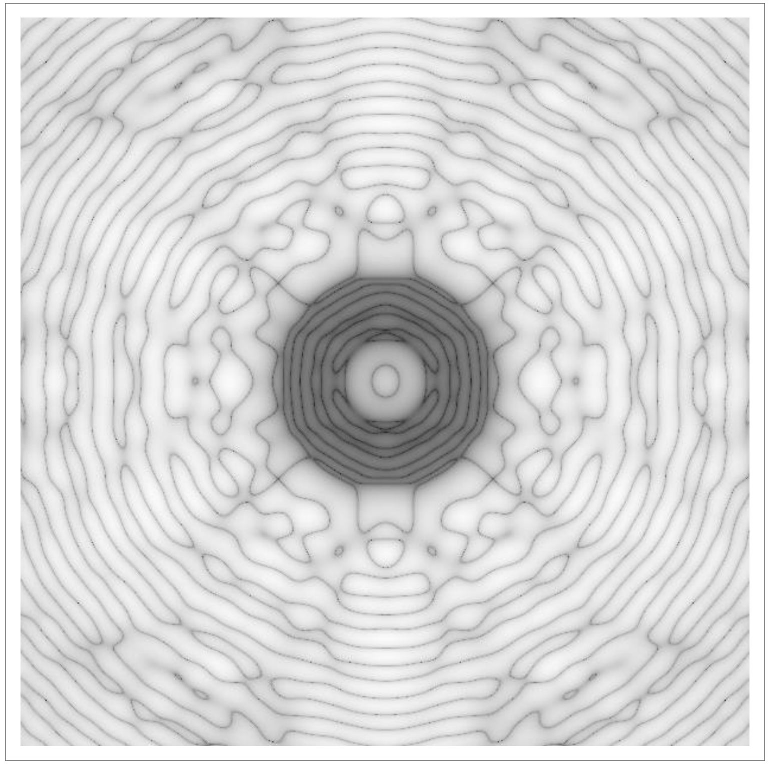
This helps to define the Mirror, backplane and control system needs

Budgets are developed based on Contrast Stability

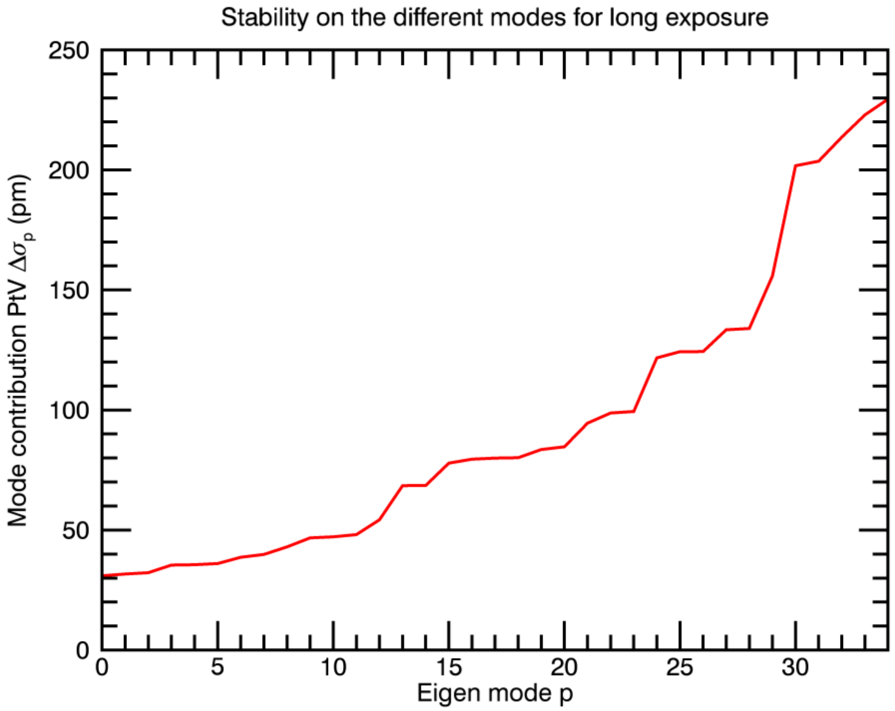
Piston Modes of Primary Mirror



MID spatial scales



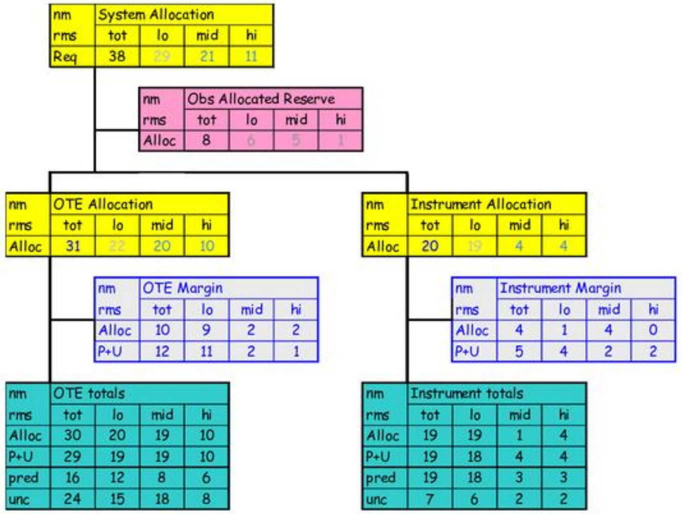
Not all pisont segment motions are equal.



This knowledge helps to define the backplane and control systems needs

Budgeting Approach/Heritage

- Approach: use a traditional branching tree structure to flow top level optical requirements down to allowable sub-system perturbations.
  - Combine errors in quadrature (reasonable assumption for complex systems).
  - Organize budget by system, sub-system, then error source.
  - Track allocations as a function of spatial and temporal frequency band.
  - Include structure for WFSC loops that will compensate for certain errors.
- Spatial Frequencies
  - lo: e.g. global low-order zernikes modes (PM+SM),
  - mid: e.g. segment-to-segment modes
  - hi: e.g. surface errors
- Temporal Frequencies
  - LF: controllable using coronagraph metrology
  - MF: controllable using telescope metrology
  - HF: uncontrolled, produces "halo" that has to be subtracted incoherently



Top Level Wavefront Error Budget for LUVOIR in picometers RMS as a function of spatial frequency.

P. Lightsey et al. "First-order error-budgeting for LUVOIR mission," *Proc. SPIE* 10398 (2017).

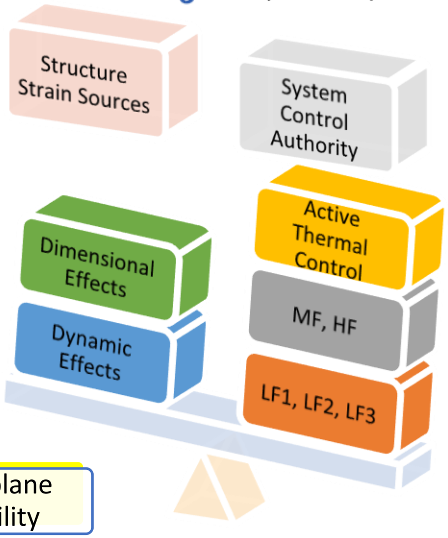
nm	System Stability			
rms	tot	lo	mid	hi
Alloc	0.034	0.025	0.020	0.011
LF	0.029	0.021	0.017	0.011
MF	0.014	0.010	0.010	0.000
HF	0.011	0.010	0.004	0.000

Sub-system requirements are used to evaluate technology/engineering gaps. The error budget is dynamic and is used to perform an analysis of alternatives via trade studies.

WFE Budget Sub-allocation to Effects Defines Initial Trade Spaces

Trade Study Budget Elements This Phase | **Active Trades This Phase**

- OTE Stability
  - PM Global Align
    - Dynamic
      - Future Work
    - Dimensional
      - Total Strain Versus Update Cycle Rates
      - Bulk CTE Implications
      - CME Design Space Options
  - PM Figure
    - Dynamic
      - PMSA Figure
      - PMSA Pose
        - Operation Disturbance Energy Level Limits
        - Sensitivity to damping
        - Bond Joint Tailoring
      - Backplane Stability
        - Future Work
    - Dimensional
      - PMSA Figure
      - PMSA Pose
        - Effective Bulk Strain Envelope Evaluation
        - Effective Bulk CTE Control Limits
        - Effective CME Strain Rate Limits
      - Backplane Stability
        - Bulk Strain Envelope Evaluation
        - Bulk CTE Control Limits
        - Bulk CME Strain Rate Limits



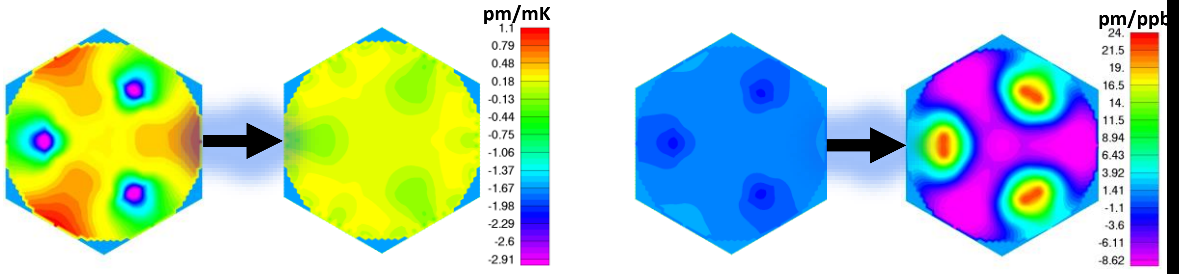
Control Bands Allocations

- LF1 < 0.001 Hz (DM in the CG)
- LF2 0.001 – 0.01 Hz (Zernike LOWFS)
- LF3 0.001 – 1 Hz (Laser Truss and Edge Sensor)
- MF 1-50 Hz
- HF > 50 Hz

- **Budgeting approach is different from past space telescopes because of the active control domains – Closer to Ground Telescopes**
- **Trade Space examines relationship between control authority and design capability**
- **Identify joint space that balances the two sides**

Mirror Figure Design Impact on Stability

What Happens When Mirror Bond is Removed?



Bulk Thermal 1mK With RTV | Bulk Thermal 1mK Without RTV | 1ppb Invar Growth With RTV | 1ppb Invar Growth Without RTV

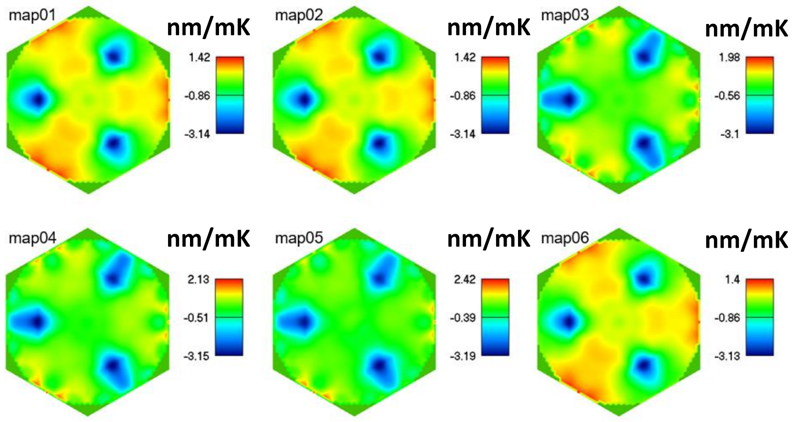
Plots: Surface Error Sensitivities - Residual After Power - With and Without RTV in Model

Knowledge of environment and material phenomena will drive design

What is the Impact of Substrate CTE Distribution?

Diff, %	GradR	GradAx	GradLat	BulkdT	FPdT	BPdT
map01	8.96%	94.77%	0.45%	1.97%	58.71%	38.68%
map02	-1.16%	5.10%	0.16%	1.97%	-27.62%	121.78%
map03	13.18%	105.10%	0.51%	9.65%	63.56%	22.35%
map04	11.98%	104.97%	2.25%	10.45%	59.90%	46.70%
map05	8.00%	101.15%	0.08%	5.25%	59.41%	138.97%
map06	-1.62%	3.70%	0.22%	1.67%	49.31%	39.54%

PMSA Figure Responses to Thermal Loads
Residual After Bias, Tilt, Power
(As Compared to 10 ppb/K Uniform Baseline)
0% Represents no Change From Uniform 10 ppb/K Baseline

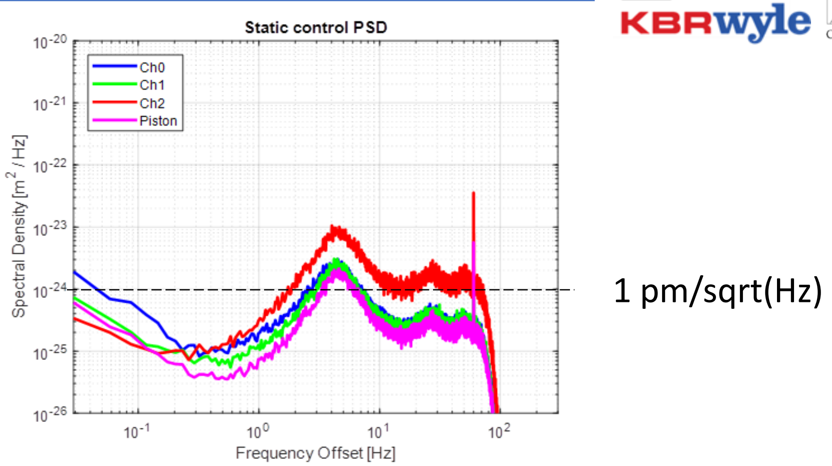


Substrate CTE variation typically penalizes performance

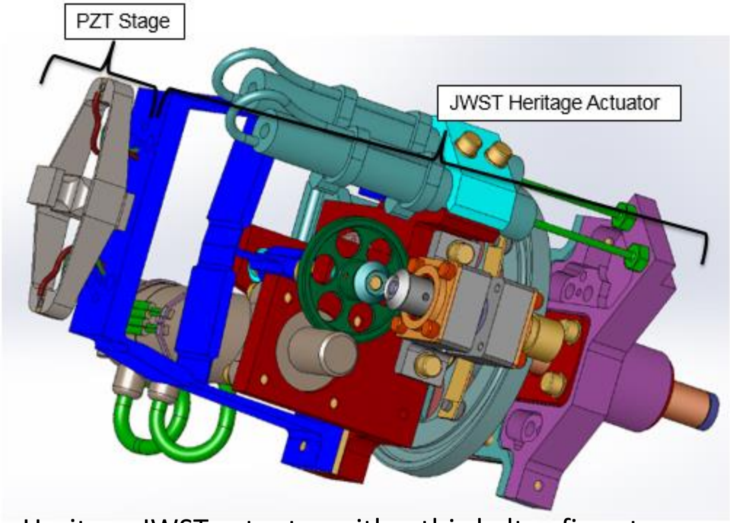
Plot: Six as-built CTE Distributions Lead to Different Sensitivities to Bulk Thermal Loads For Each PMSA

Picometer Technologies

- Sensing: Capacitive Sensor
  - Leverage existing sensor with proven ~ 10 pm RMS sensitivity
  - Characterized electronics noise: open & closed loop
  - Future work: update controller for improved performance; customize electronics for this application; larger gaps
- Control: Picometer Actuator
  - Characterize resolution, stability of ultrafine stage candidates
  - Characterize stability of JWST actuator at sub-nm level
  - Mature picometer metrology system for displacement measurements

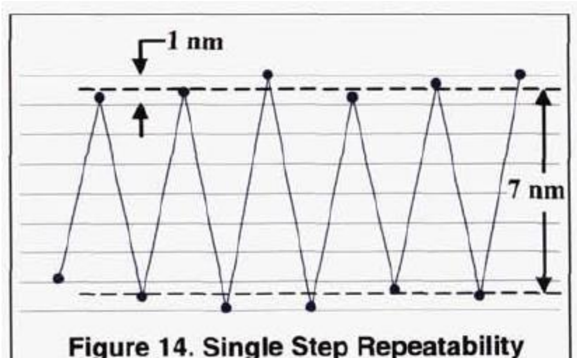


Measured Closed Loop Performance of Ball Capacitive Edge Sensor (2018)



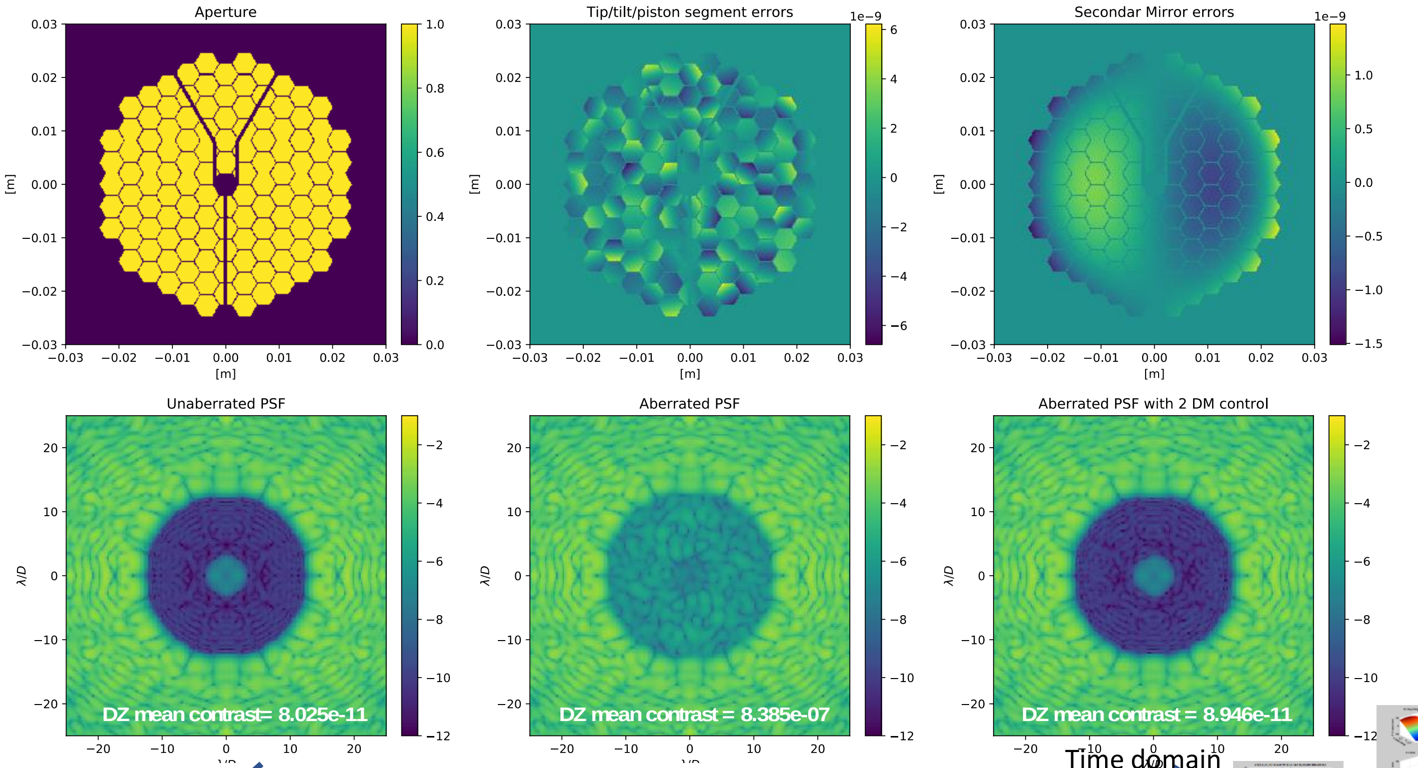
Heritage JWST actuator with a third ultra-fine stage for pm-level control.

BATC Additive Manufactured Flexures



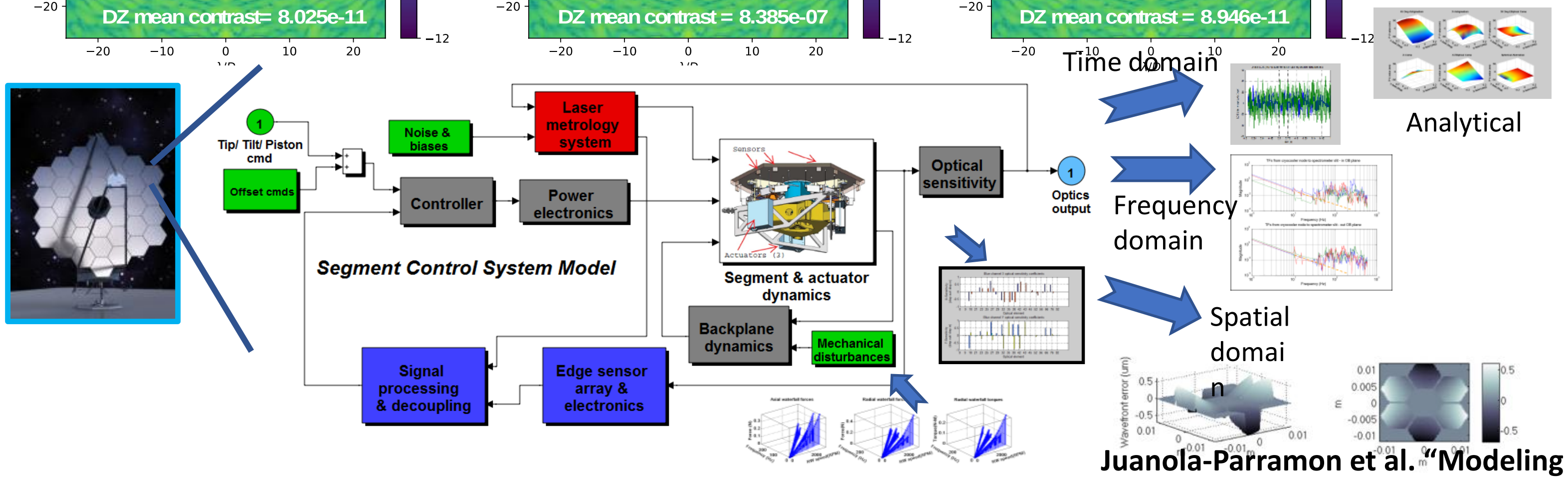
JWST Actuator Performance (Warden 2006)

Spatial Frequency End-to-End Simulation Example



IWA-OWA = 3.5 -12 λ/D, 10% bandpass
Random Tip/Tilt/Piston per segment = 1nm rms
Nact = 48 x 48
Monochromatic simulation, λ=700nm

100nm SM x-shift → Z_{coma} ~ 0.5nm rms

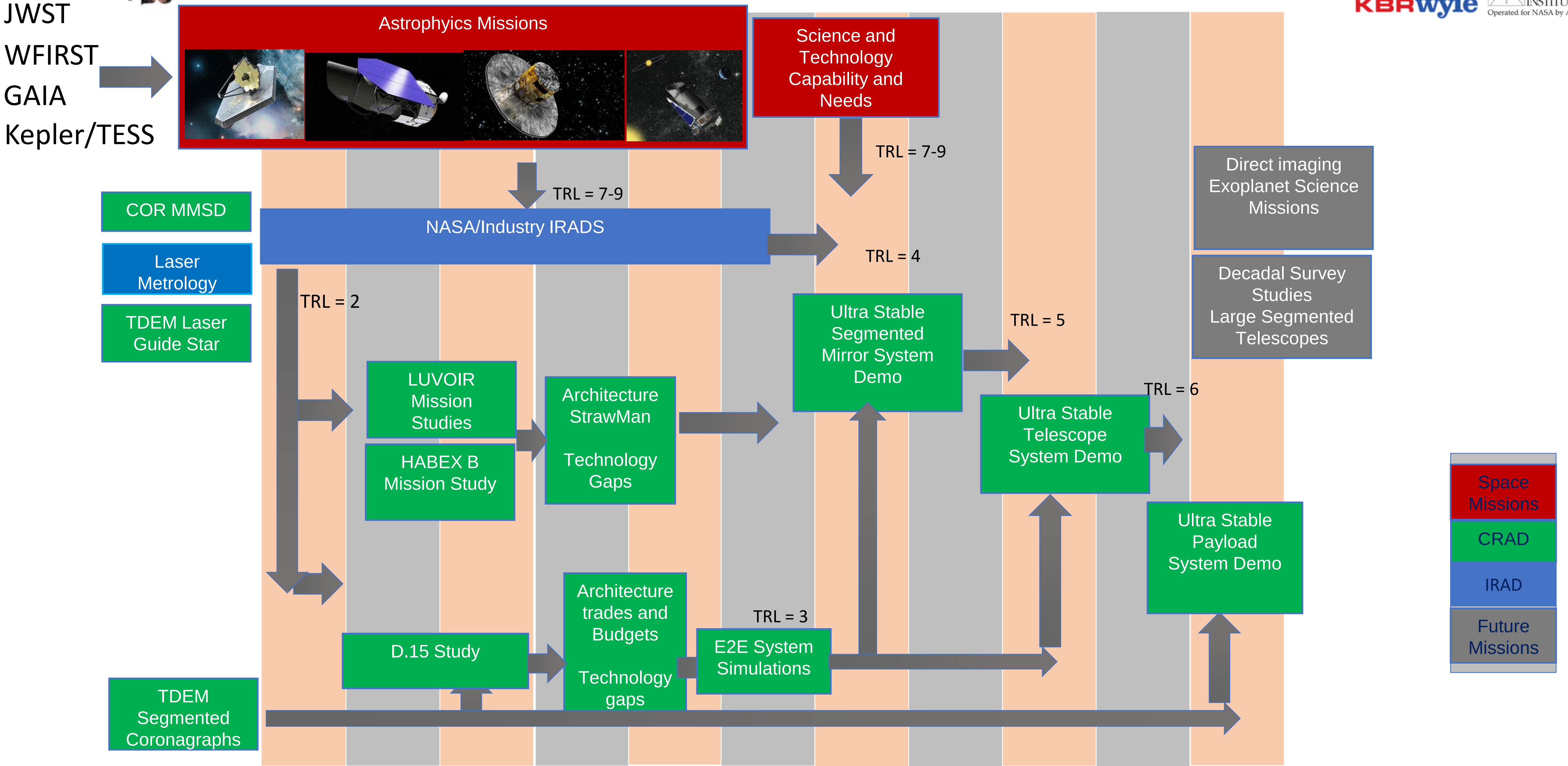


Juanola-Parramon et al. "Modeling Exoplanet Detection with the LUVOIR Telescope" (SPIE 2018)

PCOS
Physics of the Cosmos Program
COR
Cosmic Origins Program

Roadmap to Ultra Stable System

Ball HARRIS NORTHROP GRUMMAN STINGER GHAFFARIAN TECHNOLOGIES KBRwyle SPACE TELESCOPE SCIENCE INSTITUTE Operated for NASA by AURA



ULTRA Summary

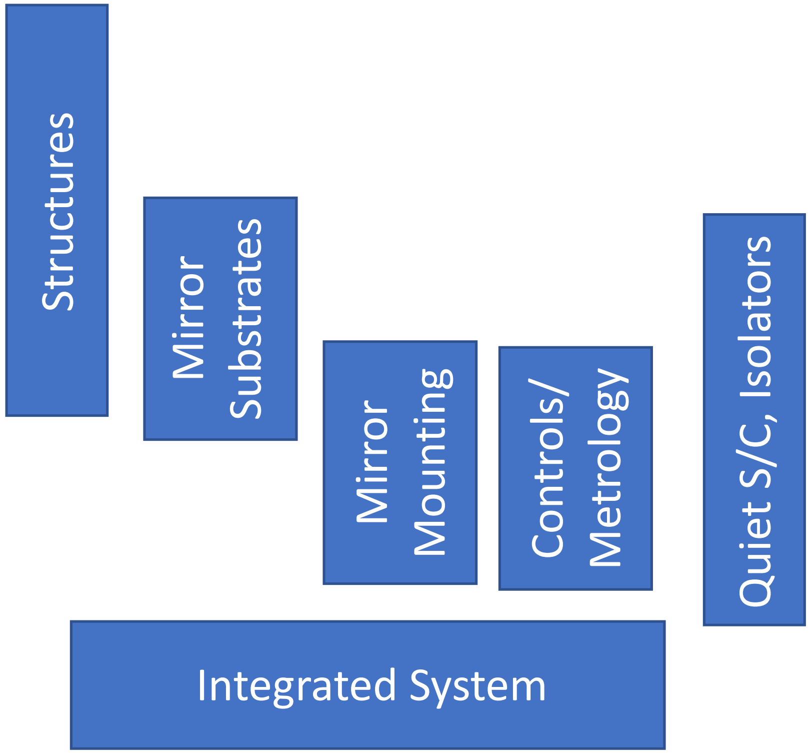
- Work in Progress:
  - Complete error budget, Assess expected disturbances and identify trade studies to identify true technology gaps.
    - Parametric/ Sensitivity Approach to Allow Trade Studies
  - Update Technology Assessment
  - Identify Technology Gaps for Mirrors, Structures, Controls at System Level
  - Revise recommended component and sub-system level testbeds based on final technology gaps.

- Path Forward:
  - Detailed planning and execution of hardware testbeds.
  - Leverage technologies and testbeds from industry, universities and NASA.

This problem is a "system of systems" - focus near term on maturing key component technologies but preserve resources for sub-system and system level validations.

ULTRA Technology Gap Definitions

Knowledge gap	We don't have measurements or knowledge at the picometer level but we don't know of anything yet that causes an issue.
Engineering / Manufacturing gap	We have a solution, but it takes engineering and process work to make sure we can build it to cost and schedule.
Mid-TRL gap	Basic Principles and performance look achievable are defined but we need development brassboards/tests to prove it in flight -like ways.
Low-TRL gap	We have solutions identified at the basic level, but need development to show they are achievable.
Architectural show-stopper	What we have won't work and we have no technologies that can make it work.



Preliminary Gap Estimate of ULTRA Study Areas

Stable Structures System Resource Allocation

Align Strain Source With Error Budget Lane

Dynamic

- On-board micro-dynamics
- Momentum transients reacted by ACS
- Gravity field transients
- Others

Dimensional

- Thermal strain response to thermal transients
- Moisture dry out effects
- Creep due to internal residual stress relaxation
- Radiation induced swelling

Dynamic Sub-allocation Approach (Work in Progress)

Align sources with temporal control categories (LF1, LF2, LF3, MF, HF)

Allocate Budgets Using Energy Distribution

Q of input work to PMSA kinetic energy and backplane strain energy

Identify Disturbance Level Thresholds vs. Design Complexity

Material Stiffness and Damping	Increased Material Damping	Added Passive Dampers	Active Suppression

Dimensional Sub-allocation Approach

Total Deformation Strain = CTE + CME + Creep + Radiation Swelling + …

Allocate Most/All Budget to CTE Effects

Balance material CTE control and system thermal control during update cycles

Identify Design Space Where Other Effects are Negligible

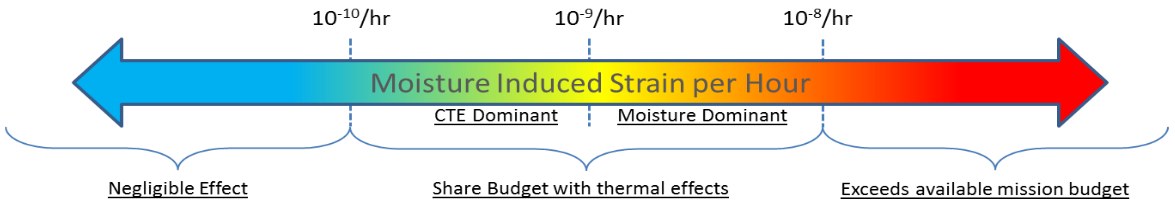
Show CME Rate < 1% of CTE Strain Rate	Show Creep + Radiation Swelling Rate + others << CME Rate

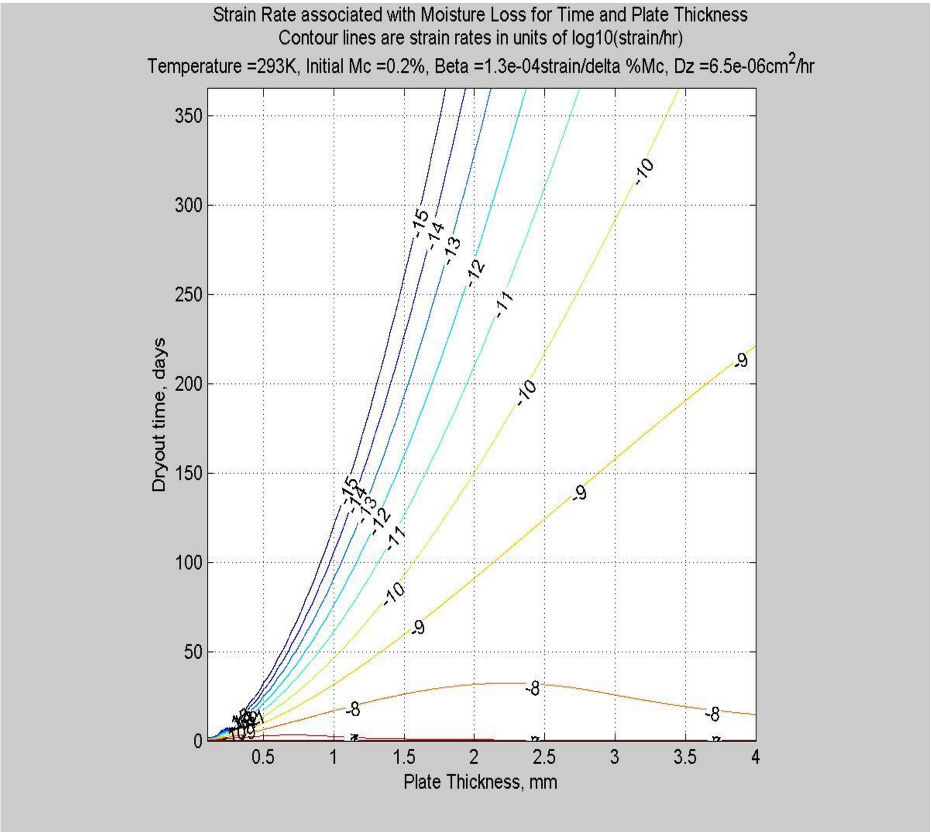
Assessment of Moisture Diffusion Effects

- Moisture strain decreases over time, Interest in strain rate after some time has passed
- Goal: < 1% total strain rate permitted by WFE budget is considered negligible
- Operating between 200 K and 273 K may require on-orbit elevated temperature dry-out assist phase
- Results to date consider PM alignment and PM Figure, PMSA Pose Decenter– update for more PM figure elements for final report

- **Available Design Space Characteristics**
  - **Thin laminates < 1.6 mm**
  - **100 day dry-out period after launch**
  - **ConOps includes on-orbit warm dry-out assist if nominal operating temperature is between 250 K and 280 K**

Path to Design Space	
Knowledge Deficiencies	Engineering Challenges
CME strain rate knowledge < 10^{-10}/hr in near-dry condition	On-orbit elevated temperature dry-out assist
Multi-phase composites for reduced D, CME and Mc	Thin laminate composite design approaches to large primary structures





LUVOIR Technology Areas – Current Assessment

Technology	*Quiet Spacecraft*	Disturbance Free Payload/Isolation	Stable Structures	Mirror Mounting	Stable Hinges/Latches	Low Disturbance Mechanisms	Stable Mirrors	PMSA Figure Actuation (if needed)	Thermal Sensing & Control	Dynamic Sensing & Control	Laser Truss	LOWFS/HOWFS	Off-Board Laser Guide Star	Infrastructure/ External Metrology	Path Forward for TRL Advancement
Current TRL	?	5	3	3	3	2	5	3	3	3	5	5	3	-	
Knowledge Gap			X	X	X	X		X	X	X					Analysis
Mid-TRL Gap				X					X						Analysis/ Subsystem Demo
Low-TRL Gap					X	X		X	X	X			x		Component-Level Demo
Engineering Gap			X				X				X		X	X	Analysis
System-Level Gap		X	X	X	X	X	X	X	X	X	X	X	X		System/ Subsystem Demos

NASA Segmented Mirror Telescope Technology: Possible Roadmap