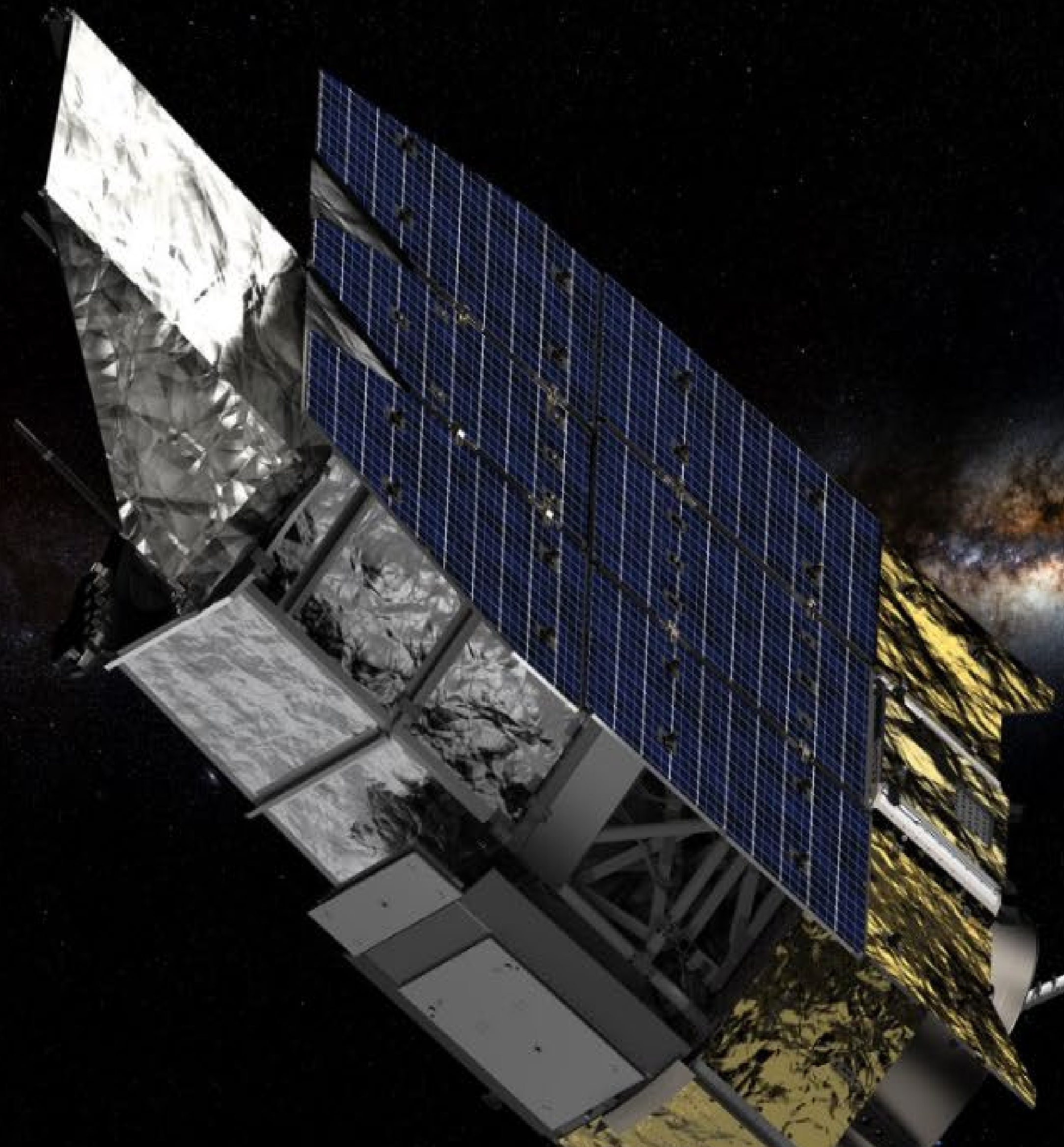
Ultra-Stable Observatory



Roman Space Telescope: Stability Performance for Coronagraph

8/10/2023

Error Budget and Integrated Modeling Lead

Kuo-Chia (Alice) Liu, Ph.D.

• NASA GODDARD SPACE FLIGHT CENTER • JET PROPULSION LABORATORY •
• L3HARRIS TECHNOLOGIES • BALL AEROSPACE • TELEDYNE • NASA KENNEDY SPACE CENTER •
• SPACE TELESCOPE SCIENCE INSTITUTE • IPAC • EUROPEAN SPACE AGENCY •
• JAPAN AEROSPACE EXPLORATION AGENCY • LABORATOIRE D'ASTROPHYSIQUE DE MARSEILLE •
• CENTRE NATIONAL d'ÉTUDES SPATIALES • MAX PLANCK INSTITUTE FOR ASTRONOMY •

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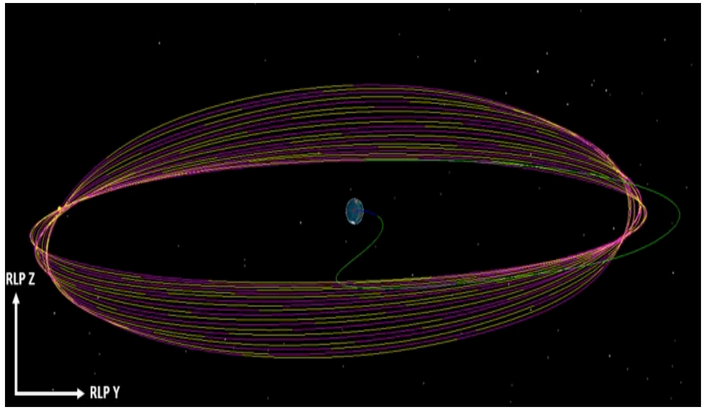
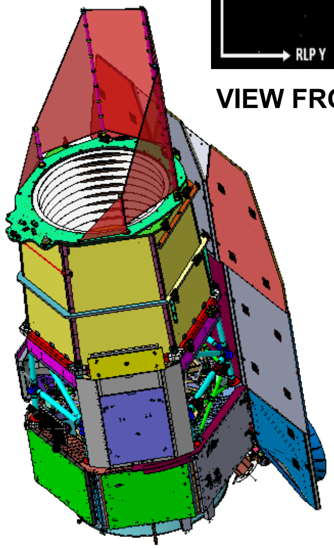
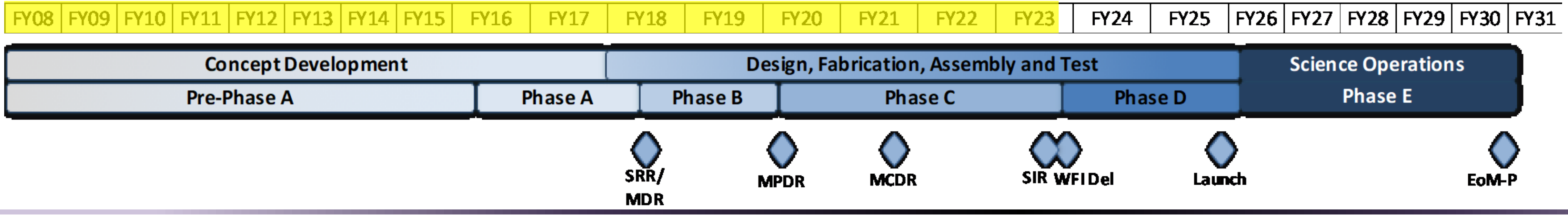
Roman Mission Overview

- **RST:** Nancy Grace Roman Space Telescope (Class A)
- **Mission:** Wide-Field Infrared Survey
- **Objectives:**
  – Determine the nature of the dark energy that is driving the current accelerating expansion of the universe
  – Perform statistical census of planetary systems through microlensing survey
  – Survey the NIR sky
  – Provide the community with a wide field telescope for pointed observations
  – Fly a technology demonstration of a high-contrast coronagraph instrument
- **Mission Duration:** 5 years science
- **Orbit:** Quasi-Halo Orbit about Sun-Earth L2
- **Launch Vehicle:** Falcon Heavy
- **Launch Site:** Eastern Range
- **Mission Budget:** $3.3 Billion through Phase E
- **Mass:** 10,750 kg (NTE)
- **LRD:** October 2026



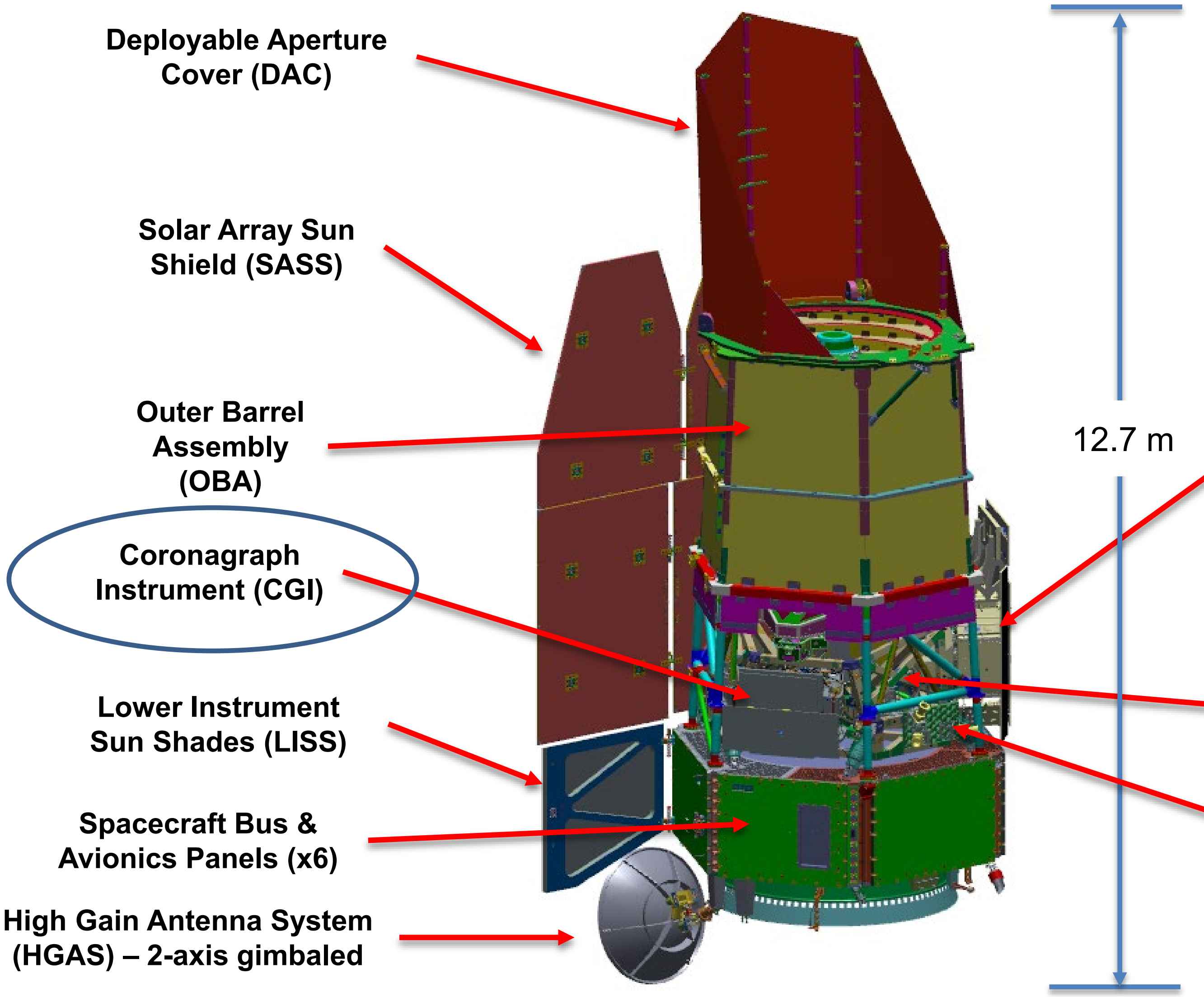
VIEW FROM EARTH TO L2

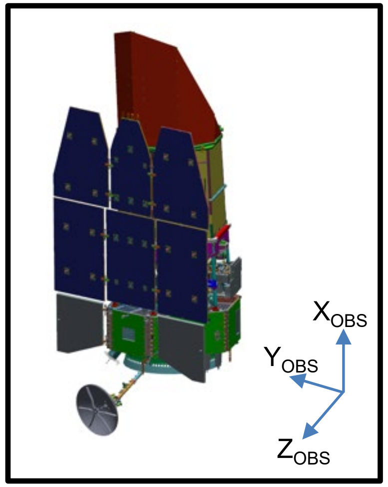




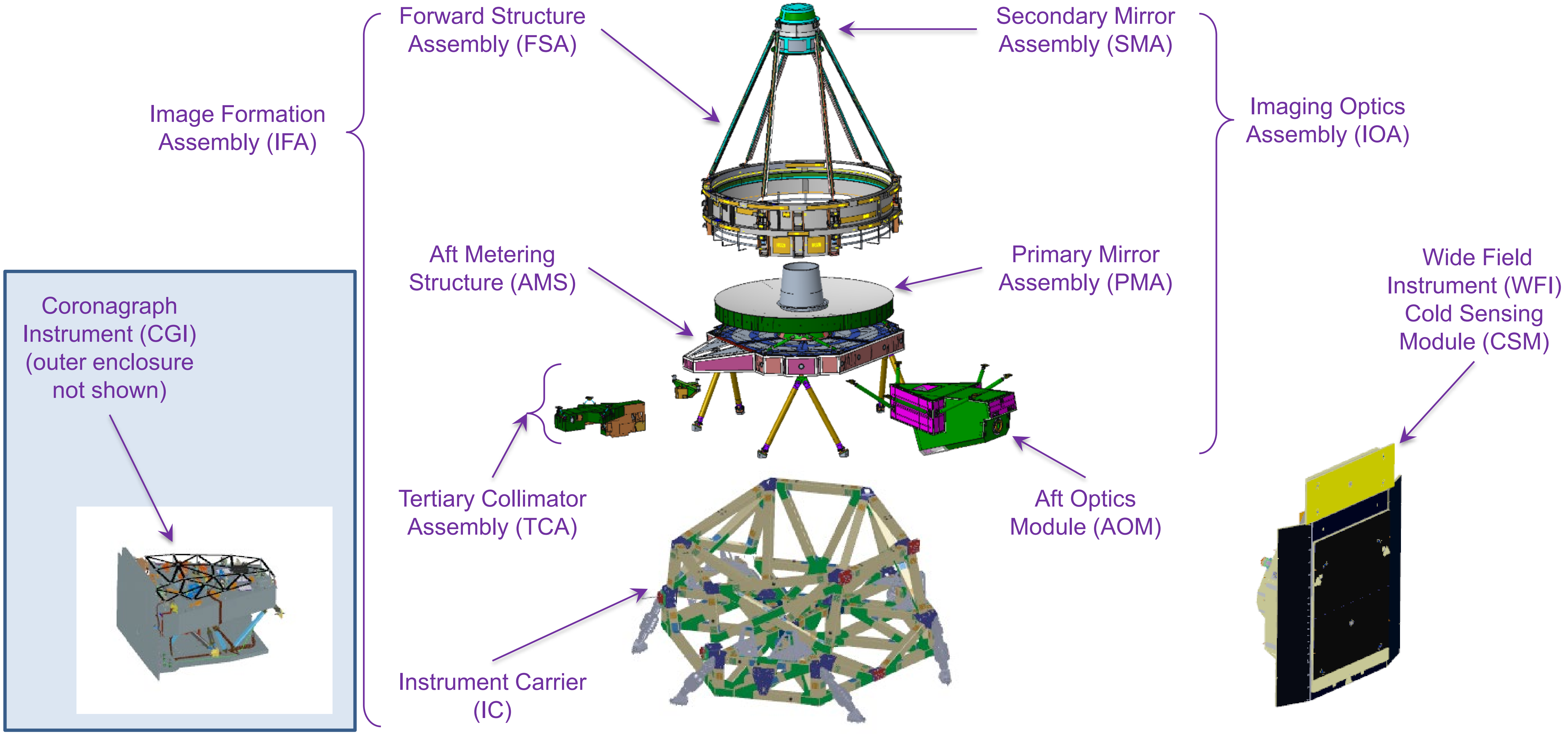
ROMAN SPACE TELESCOPE

Observatory Overview

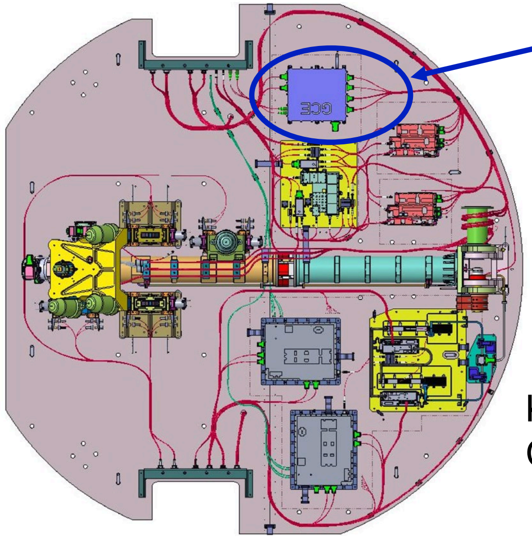




Integrated Payload Assembly (IPA)



Spacecraft



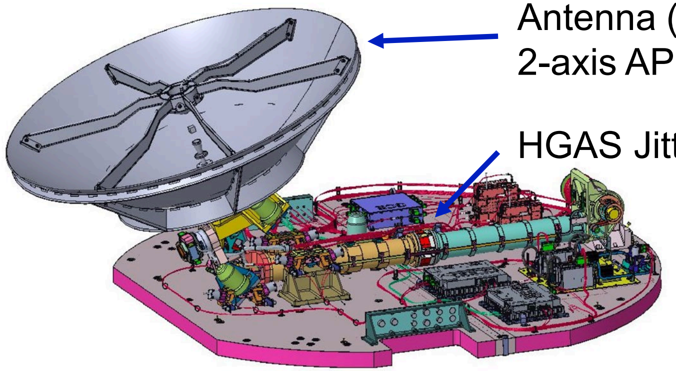
GCE

S-band Components

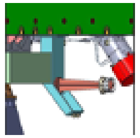
Ka-band Components

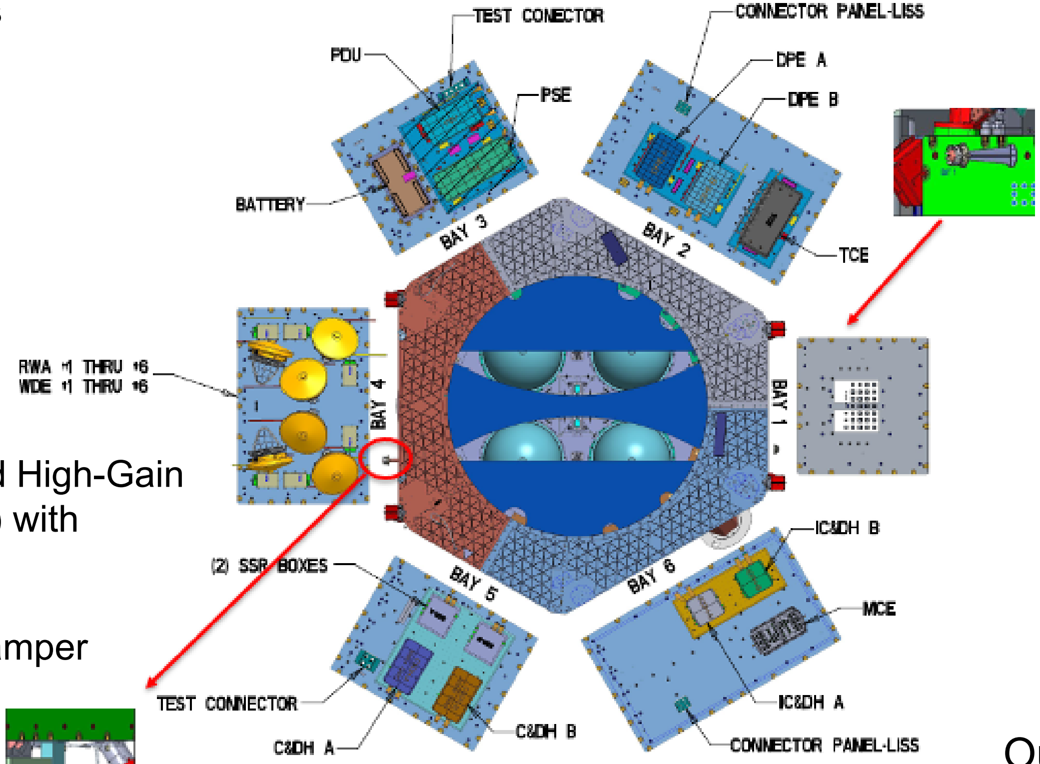
1.7m dual-band High-Gain Antenna (HGA) with 2-axis APS

HGAS Jitter Damper



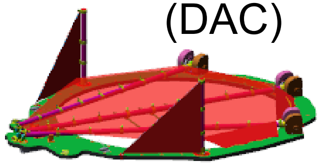
Communications Panel (internal to LV adapter)

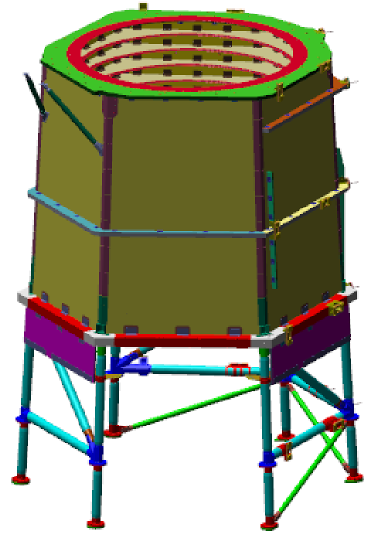


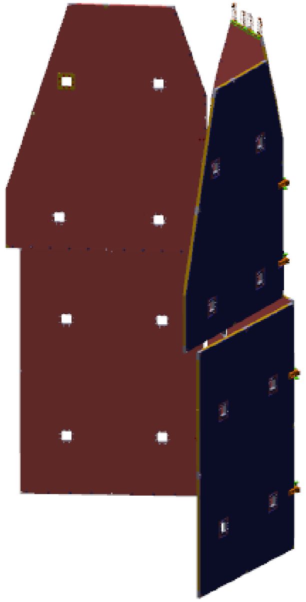


Spacecraft Bus

Deployable Aperture Cover (DAC)







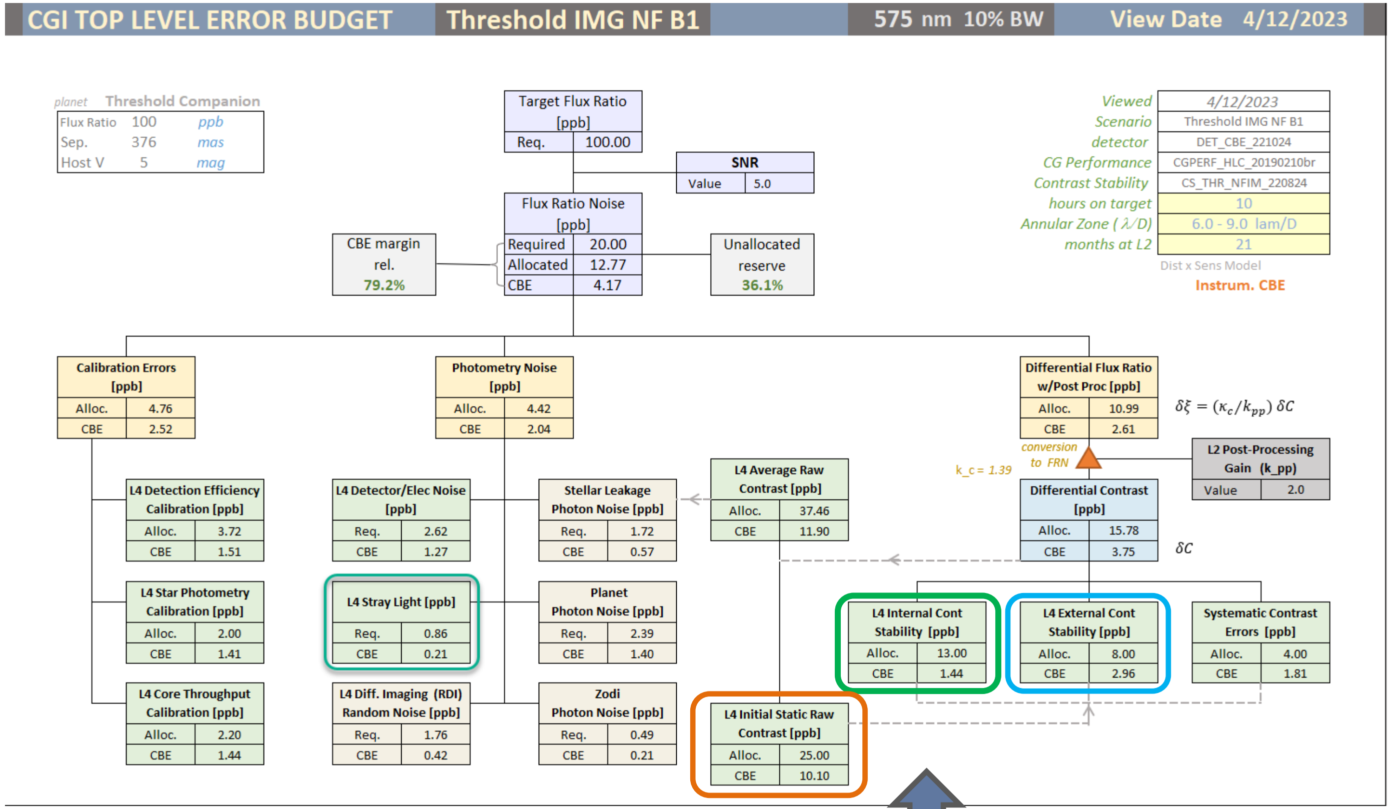
Solar Array Sun Shield (SASS)

Outer Barrel Assembly (OBA)

OBA/SASS/DAC (OSD)

CGI Top Level Error Budget and Stability

- **CGI stability requirements flow from Flux Ratio Noise (FRN) error budget**
  - Contrast sensitivities, derived from optical diffraction models set in PROPER tool, have been validated against the coronagraph testbed
  - MUF = 2 is used on sensitivities



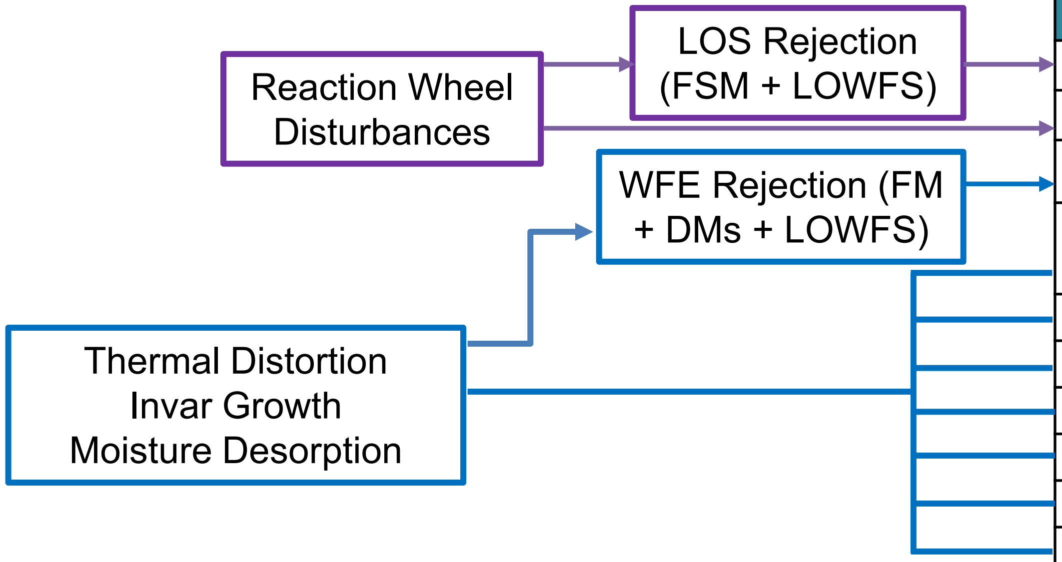
Focus of Presentation

- L4 Initial Static Raw Contrast: quasi-static conditions
- L4 External Contrast Stability: Effects due to Observatory stability during an observing scenario, which CGI must suppress using internal control loops and/or accommodate
- L4 Internal Contrast Stability: Effects due to CGI internal stability, such as DMs, optical bench, etc

Optical Stability Budget - Coronagraph

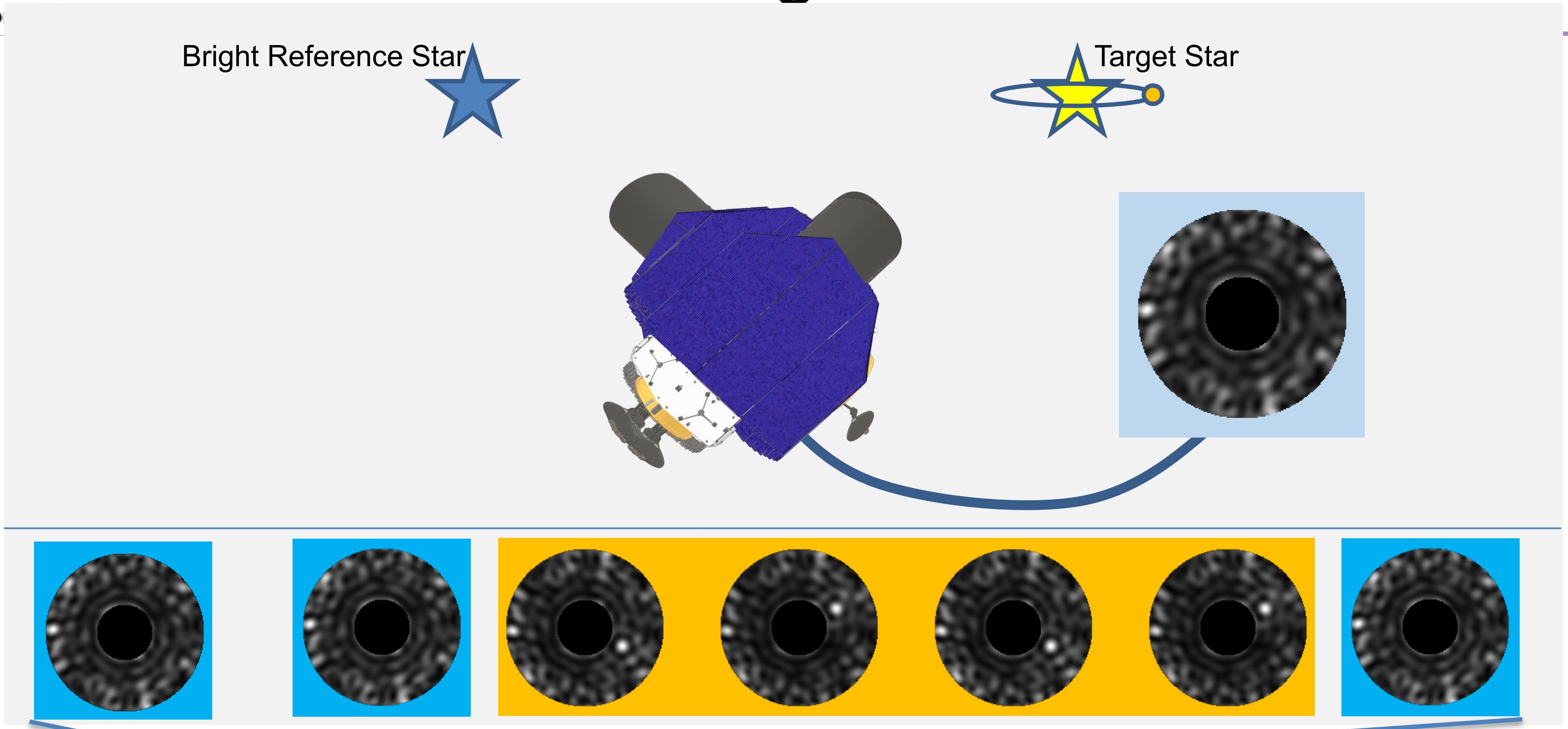
- **CGI relies on observatory stability to meet technology demonstration goals**
  - Observatory is designed to meet Wide Field science requirements

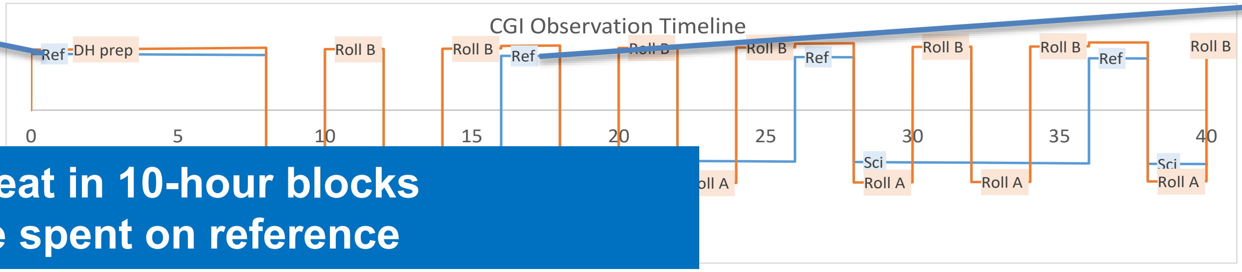
- **CGI stability requirements are met by using CGI internal controllers and observatory operational capabilities**
  - LOS jitter rejection achieved by fast steering mirror (FSM) and low-order-wavefront-sensor (LOWFS)
  - WFE drift rejection through focus mechanism (FM) and deformable mirrors (DMs)
  - Constrain wheel speeds
  - Avoid moving HGA during exposures
  - CGI stability requirements only need to be met for ≥70% of images



Coronagraph Stability (10-hour)	
Stability Requirements	Requirement
Filtered LoS Drift + Jitter [mas]	0.57 >70% of time
WFE Jitter Z4-11 [nm]	0.25
Filtered Z4-11 WFE Drift [nm]	0.15
Z4 WFE Drift [nm]	10 (100-hour) 4.0 (10-hour)
RSS(Z5-11) WFE Drift [nm]	0.25
Pupil Shear Drift Mean [um]	0.70
Pupil Shear Drift Delta Mean[um]	0.40
Chief Ray Angle of Incidence Mean [mas]	7.0
Chief Ray Angle of Incidence Delta Mean [mas]	5.0
CGI-to-WFI Boresight Rate of Change [mas]	10.0

Observing Scenario





differences repeat in 10-hour blocks
10-20% of time spent on reference

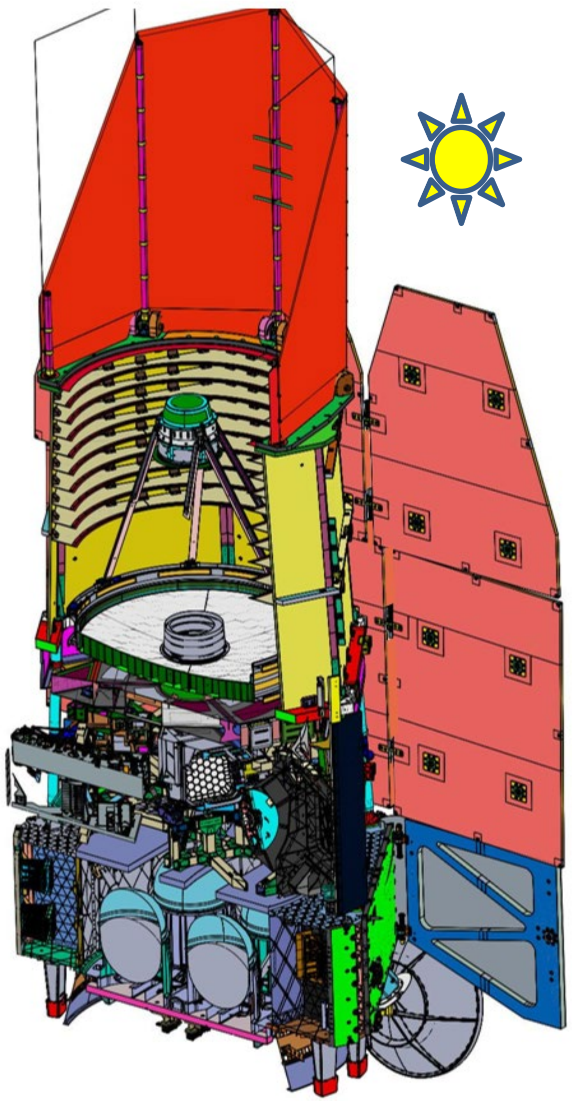
RDI Output:

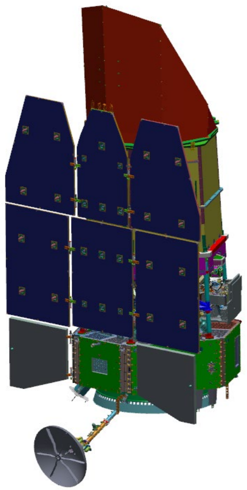
Observing Scenario Designed for RST+Coronagraph Stability in the Reference Differential Imaging Context

Stability Perturbations and Mitigations
Structural-Thermal-Optical (STOP) and Distortion

Perturbations

- **Ground to orbit**
  - Cooldown
  - Gravity release
- **On-orbit variations**
  - Thermal due to change in environment
  - Thermal due to internal heat load variations
  - Hygroscopic dryout
  - Invar growth
  - BOL to EOL material property changes

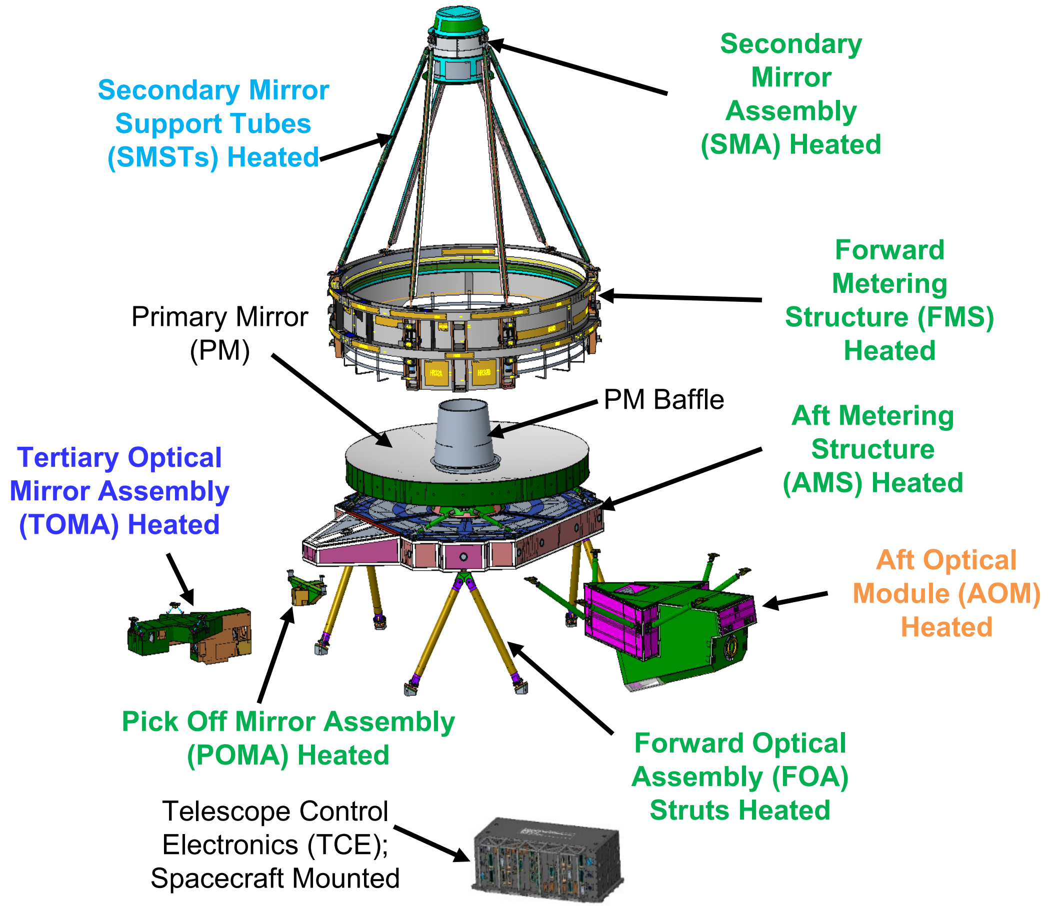




- **Ground-to-orbit**
  - Place optics at predicted 1G and warm positions to offset gravity and cold-shift effects
  - Cold figure primary mirror
  - Thermal control system
  - Kinematic interfaces (FOA struts and WFI outer enclosure)
  - Flight Alignment compensators
- **Thermal/Thermoelastic Stability**
  - Mechanical sun shields
    - Solar Array and Sun Shield (SASS)
    - Deployed Aperture Cover (DAC)
      - Low emissivity
    - Outer Barrel Assembly (OBA)
    - Lower Instrument Sun Shade (LISS)
  - Thermal control systems
    - OBA, IOA, IC, WFI, CGI, and SC Bay 4
  - Active optics control
    - CGI focus mechanism and deformable mirrors
  - ConOp constraints
    - Reduce slew size and observing plans
- **Long-term material and/or dimensional stability**
  - Flight alignment compensators

Optical Telescope Assembly: Thermal Management System

- TMS is cold-biased design supplemented with heater control to provide a stable OTA in all specified environments
  - Each heater zone has independent PI thermal control during all phases of mission
  - IOA has multiple temperature-controlled zones
- Outer Barrel Assembly (OBA) provides FOA with a stable, 230 K thermal environment
  - MLI Closeout between AMS and OBA limits FOA's radiative exposure to uncontrolled environments
- Observatory's most thermally sensitive components include the PM, SM, and SMSTs
  - STOP analysis has shown that these components require ~10 mK level stability to meet optical requirements
  - Sub-milli-Kelvin temperature stability capability was demonstrated with a flight-like integrated thermal control system (Roman DITS)
- AOM, POMA, and TOMA are separate optical assemblies located on the aft side of the AMS with their own operating temperatures / thermal designs.
  - TOMA includes a tip/tilt fold mirror to correct pupil shear
  - Each rely on their MLI-blanketed enclosures as radiators to provide sufficient cold-biasing for positive heater control



Heater Set Points

AOM Heaters @ 218K Set Point

AMS, FMS, FOA Strut, SMA & POMA Heaters @ 266.5K Set Point

SMST Heaters @ 269K Set Point

TOMA Heaters @ 293K Set Point

Requirement Verification Approach and Model Uncertainty

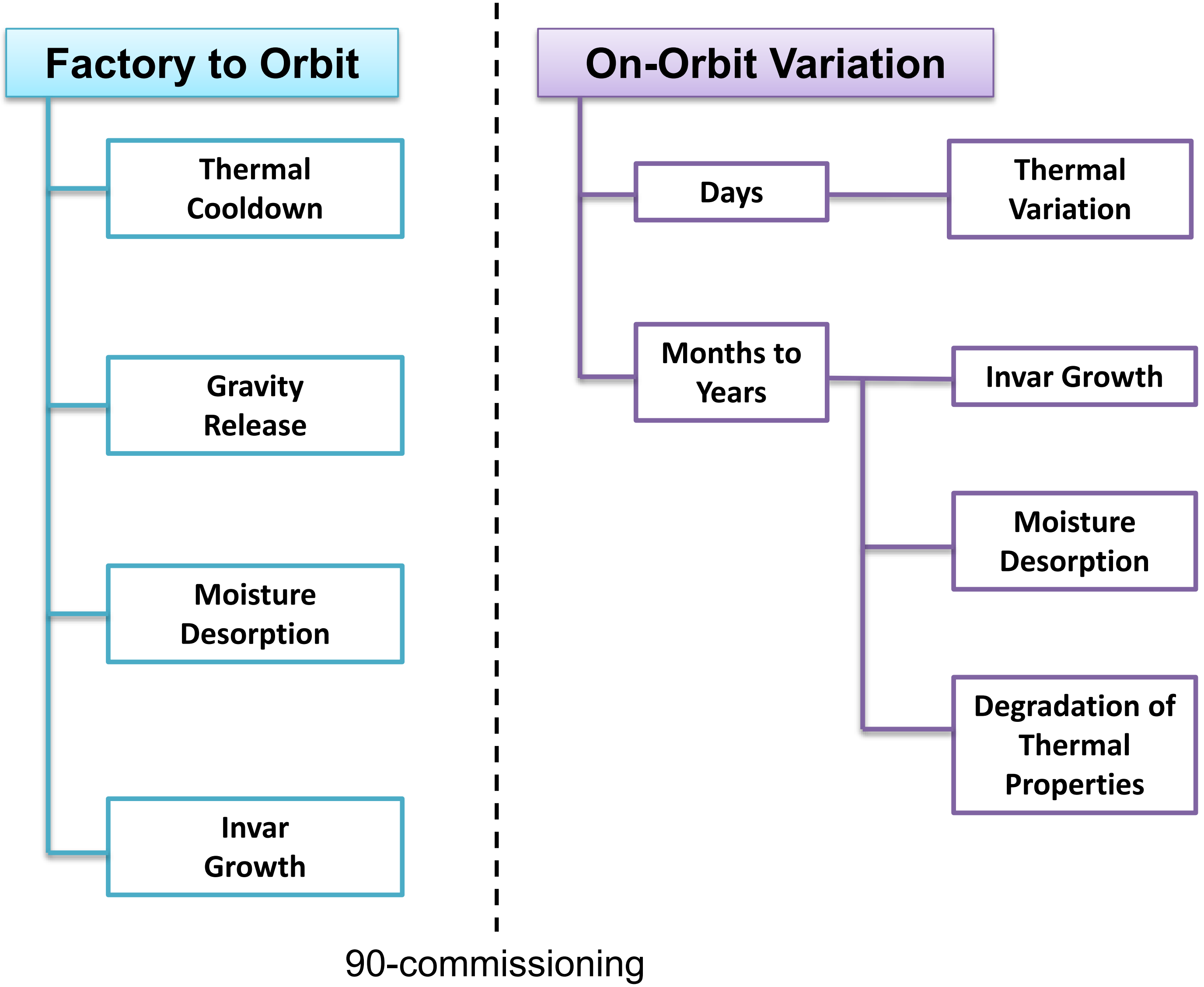
- **Analysis is a key verification approach for stability requirements**
- **For requirements verified by analysis, all performance predictions include model uncertainty**
- **Model uncertainty can be incorporated by using worst case assumptions, model uncertainty factor (MUF), or Monte Carlo analysis**
  - Optical analysis uses Monte Carlo approach to capture reasonable fabrication and alignment tolerances
  - Thermal analysis uses worst case assumptions
  - Distortion and dynamic analyses use MUF to capture reasonable parameter variations (CTE, moduli, etc.)
- **Roman uses structural Monte Carlo analysis to determine appropriate MUFs for analysis predictions**

Distortion Analysis	MUF (Phase C – CDR)
STOP	
Cooldown	2 (rigid-body)/1.3 (figure)
WFI and Pupil Stability	2 (rigid-body)/1.3 (figure)
Pupil Clocking	2
LOS drift	4
Gravity Sag and Release	0.1 (alignment) 2 (figure)
Moisture Desorption	2
Invar Growth	1.1

Jitter Analysis	MUF (Phase C – CDR)
Reaction Wheel and HGAS Jitter	3.0 (<50 Hz)
	3-8 (40-100 Hz)
	8.0 (100-325 Hz), 10 (>350 Hz)

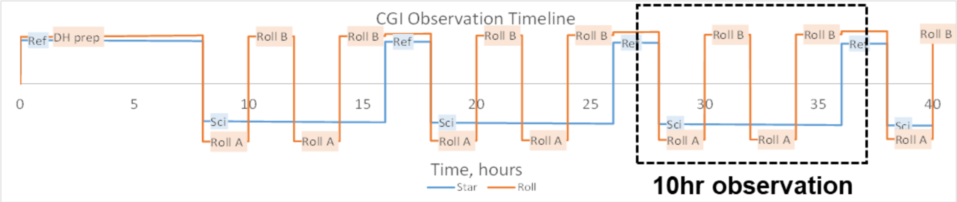
Structural Distortion Analyses Relevant to Optical Performance

- **IM STOP analysis includes structural distortion from the following sources**
- **Thermal distortion**
  - Dimensional changes due to changes in temperature
- **Moisture desorption**
  - Dimensional changes due to outgassing of moisture from composite components
- **Gravity release**
  - Calculates "locked" strains from the in-gravity integration process
  - Evaluates dimensional changes created by the locked strains once gravity is removed
- **Invar growth**
  - Dimensional changes due to the propensity of Invar to expand after manufacture



Structural-Thermal-Optical (STOP) Analysis Flow

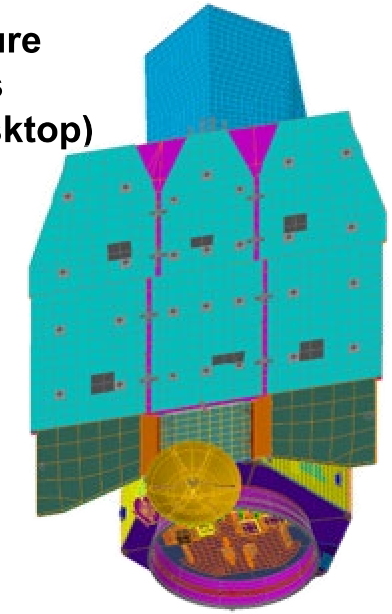
Observational Scenario (OS)



OS11 Includes both external (eg. sun angle) and internal (eg. electronics dissipation) disturbances

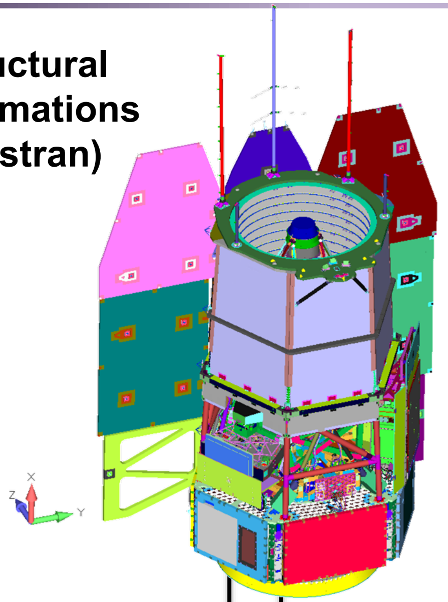
Disturbances

Temperature Predicts (Thermal Desktop)



Temp. Map

Structural Deformations (Nastran)



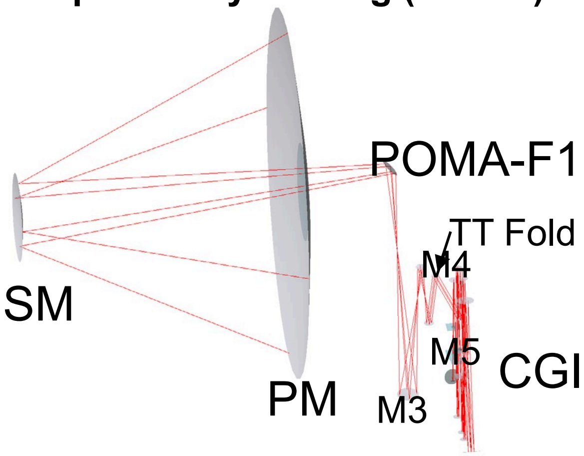
Nodal deformations

Opto-Mechanical Software

Optical Pre-Processing (SigFit)

- 6DOF motion of individual optics in local CSYS

Optical Ray-Tracing (CodeV)



CGI Performance Predictions

- Wavefront Error
- Pupil Shear / Clocking
- Image Motion @ Cameras
- Chief Ray Angle of Incidence

EllipTool

Linear Optical Model

CGI Stability Performance Summary

- **Tight CGI stability requirements are met with MUFs and reasonable margins except for 100-hour Z4 stability**
  - As presented at Mission CDR, slight exceedance of Z4 drift over 100 hours is acceptable
  - Continue to investigate methods to reduce moisture desorption analysis conservatism
- **Bay 4 Bus heater control improvement greatly reduced boresight rate of change error**
  - Reduction of a factor of ~4 from CDR prediction

Req	Description	Units	Alloc	CDR (Cy2)	Cy3.1	% Margin
MRD-498	**CGI WFE Drift, Starlight Suppression, 100 hr**	**nm**	**10**	**10.01**	**12.14**	**-**
	Thermal Variation	nm		2.50	2.50	
	Moisture Desorption	nm		7.31	9.40	
	Invar Growth	nm		0.20	0.24	
MRD-502	**CGI to WFI Boresight Rate of Change**	**mas/hr**	**10**	**20.21**	**5.18**	**48.15%**
	Thermal Variation	mas/hr		20.20	4.48	
	Moisture Desorption	mas/hr		0.01	0.70	
	Invar Growth	mas/hr		4.00E-03	4.72E-03	

Requirement	Description	Units	Alloc	CDR (Cy2)	Cy3.1	% Margin
MRD-489	**CGI Pupil Lateral Stability - Mean**	**um**	**0.7**	**0.50**	**0.51**	**27.31%**
	Thermal Variation	um		0.49	0.49	
	Moisture Desorption	um		0.01	0.01	
	Invar Growth	um		1.00E-03	4.80E-03	
MRD-490	**CGI Pupil Lateral Stability - Delta Mean**	**um**	**0.4**	**0.14**	**0.08**	**79.50%**
	Thermal Variation	um		0.14	0.08	
	Moisture Desorption	um		2.70E-06	1.00E-05	
	Invar Growth	um		0.00E+00	0.00E+00	
MRD-500	**CGI Chief Ray Angle of Incidence Stability: Mean**	**mas**	**7**	**2.64**	**1.21**	**82.76%**
	Thermal Variation	mas		2.48	1.14	
	Moisture Desorption	mas		0.16	0.06	
	Invar Growth	mas		6.00E-05	4.10E-03	
MRD-501	**CGI Chief Ray Angle of Incidence Stability: Delta-Mean**	**mas**	**5**	**0.72**	**0.46**	**90.82%**
	Thermal Variation	mas		0.72	0.46	
	Moisture Desorption	mas		4.30E-05	1.20E-04	
	Invar Growth	mas		0.00E+00	0.00E+00	
MRD-495	**CGI Z5-Z11 WFE**	**pm**	**250**	**79.79**	**97.71**	**60.92%**
	Thermal Variation	pm		57.80	75.33	
	Moisture Desorption	pm		21.19	21.58	
	Invar Growth	pm		0.80	0.80	
MRD-496	**CGI Corrected WFE Drift, Z4-Z11**	**pm**	**150**	**7.80**	**23.99**	**84.01%**
	Thermal Variation	pm		7.80	21.15	
	Moisture Desorption	pm		1.60E-04	2.84	
	Invar Growth	pm		2.00E-05	3.34E-05	
MRD-498	**CGI WFE Drift, Starlight Suppression, 10 hr**	**nm**	**4**	**1.22**	**1.16**	**70.99%**
	Thermal Variation	nm		0.04	0.19	
	Moisture Desorption	nm		1.17	0.95	
	Invar Growth	nm		0.02	0.02	

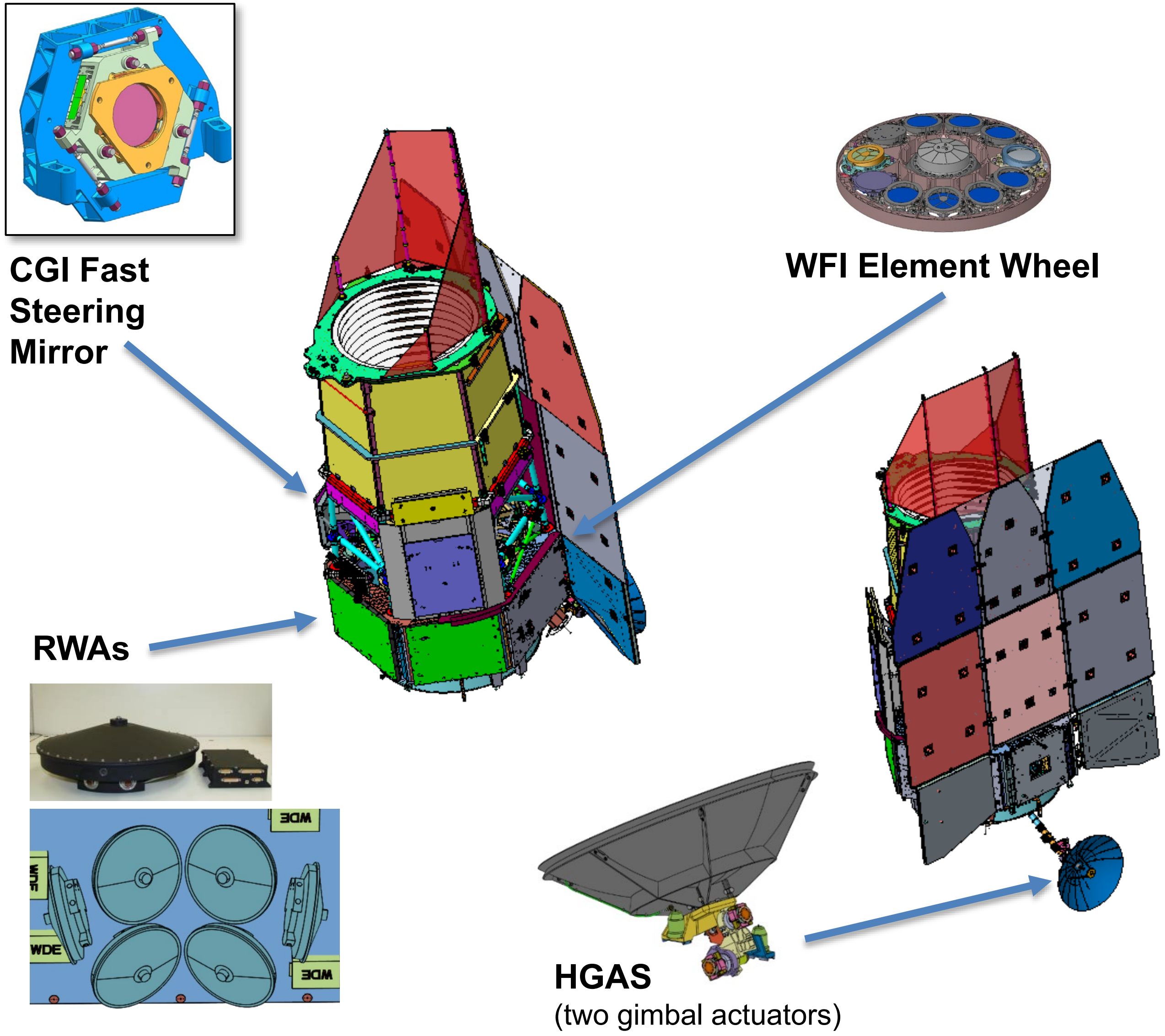
Major Dynamics Error Sources

- **Reaction Wheel Assemblies**
  - Six Honeywell HR18-250 RWAs
  - Fine balance option for reduced static/dynamic disturbance

- **High Gain Antenna System (HGAS)**
  - Two axis gimbal using low-detent stepper motors to provide gimbal pointing
  - The antenna **rarely would need to be moved *during imaging***

- **WFI Element Wheel (EW)**
  - Stepper motor used to place the desired optic into the light path
  - ***Will not operate during imaging***

- **CGI Fast Steering Mirror (FSM)**
  - Reaction compensated tip/tilt mirror
  - ***Self-induced disturbance, managed by CGI***
  - Note: much less contribution from other, smaller mechanisms (Focus and DMs)



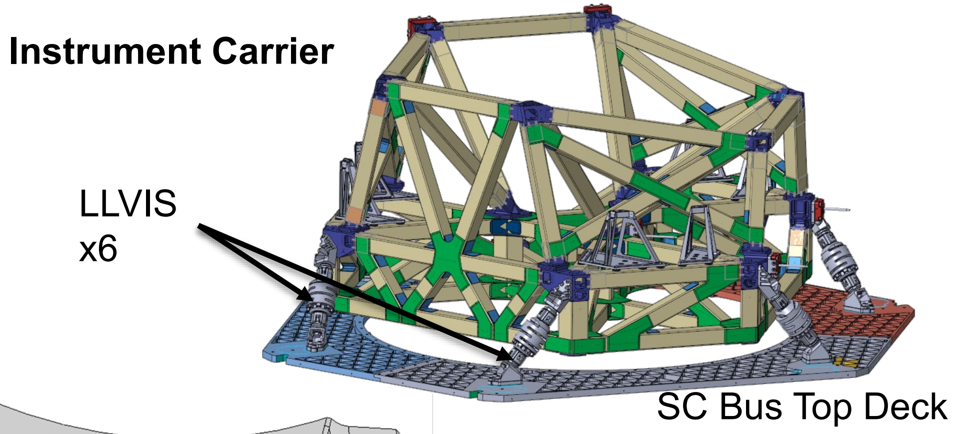
Dynamics Mitigations

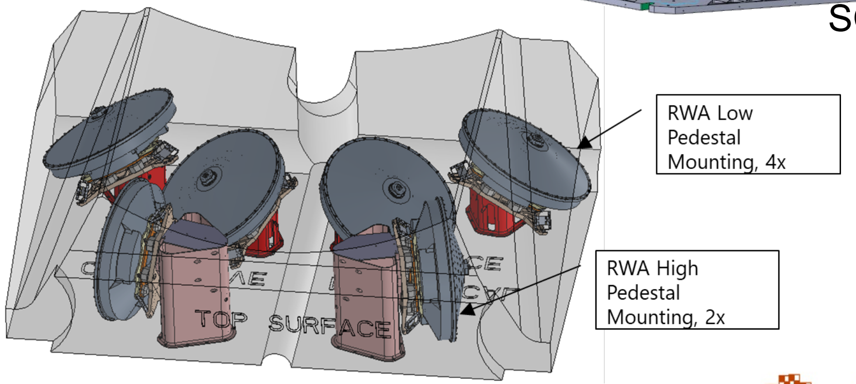
- **Launch Loads and Vibration Isolation System (LLVIS)**
  - Between the SC and IC, ***Honeywell*** D-strut heritage
  - ~20 Hz first mode, attenuates RWA and HGS disturbances

- **Reaction Wheel Jitter Mitigation Implementations**
  - Each RWA is individually isolated, ***Moog CSA*** SoftRide heritage
  - RWA speeds are limited to 5 rev/sec (30 RPM) during CGI operation to avoid exciting resonant modes above this frequency
  - ACS is using an L-infinity wheel distribution algorithm that drives four wheels to the same speed
  - ACS is enforcing 1 Hz (60 RPM) separation between the four wheels

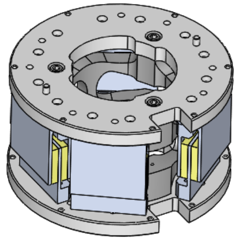
- **HGAS Jitter Mitigation Implementations**
  - HGAS Jitter Damper (HJD) developed by ***Moog CSA***
    - Damps out HGAS boom modes excited during HGAS operation
  - Actuator microstepping; 16 micro-steps per every detent step
  - HGAS step avoidance during inertial hold
    - ACS is designing their HGAS pointing algorithm and slew profile to minimize the need to step during imaging
  - HGAS step rate keep out zone
    - Accelerate through problematic mode frequencies to avoid ringing up the modes

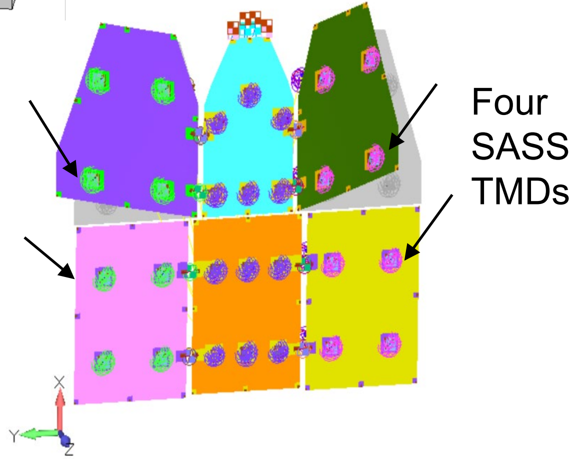
- **Solar Array Sun Shield (SASS) Tuned Mass Dampers (TMDs)**
  - ***Under development by Moog CSA***
  - Damps out SASS modes excited during wheel and HGAS operations



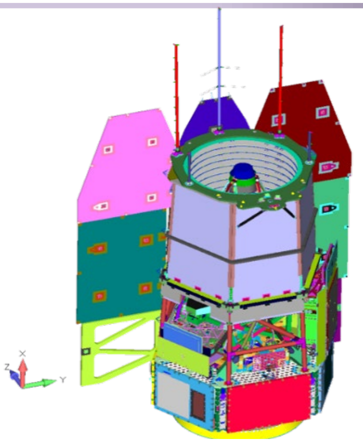


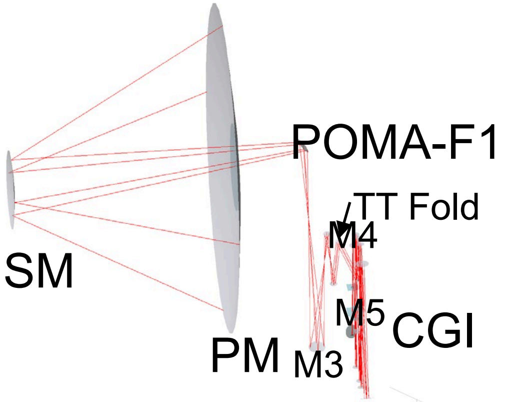
HGAS Jitter Damper

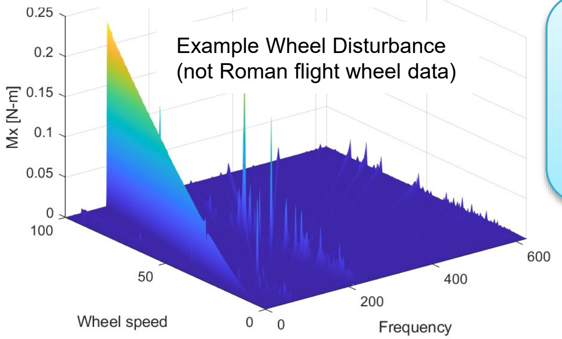




Jitter Analysis Flow







Structural Model (NASTRAN) → Normal Modes Analysis → Eigenvalues and Eigenvectors → State-Space Model

Structural dynamics are represented by Normal Modes data from the NASTRAN Finite Element Model

Optical Model (Code V) → Sensitivity Analysis → Linear Optical Model → State-Space Model

Optical responses are computed with a Linear Optical Model that is integrated to the structural dynamics

State-Space Model → Jitter Analysis (EllipTool: Time or Frequency Domain)

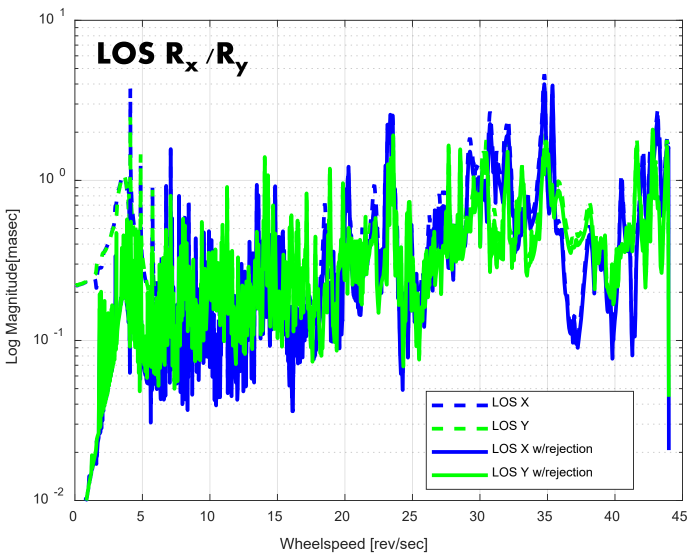
Disturbance Model (Matlab) → Jitter Analysis (EllipTool: Time or Frequency Domain) → LOS Jitter and WFE Jitter (versus wheel speed and envelope versus frequency)

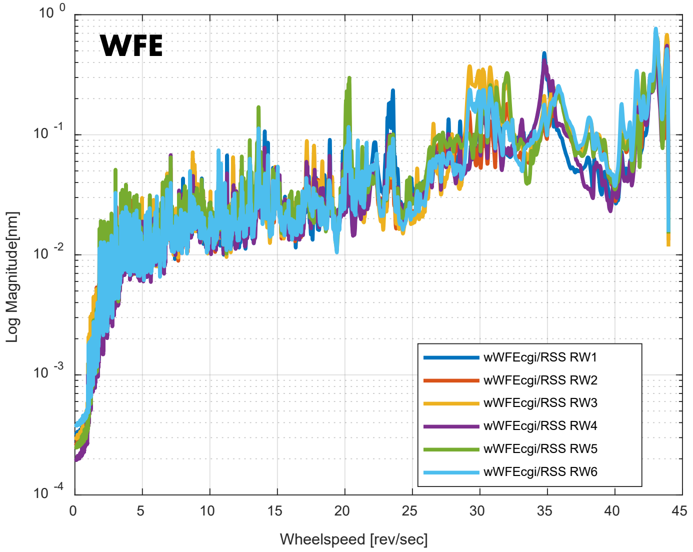
Frequency domain (reaction wheel, facility noise) and time domain (stepper mechanism) disturbances are impinged on the integrated model to produce optical response predictions

CGI Jitter due to Reaction Wheels

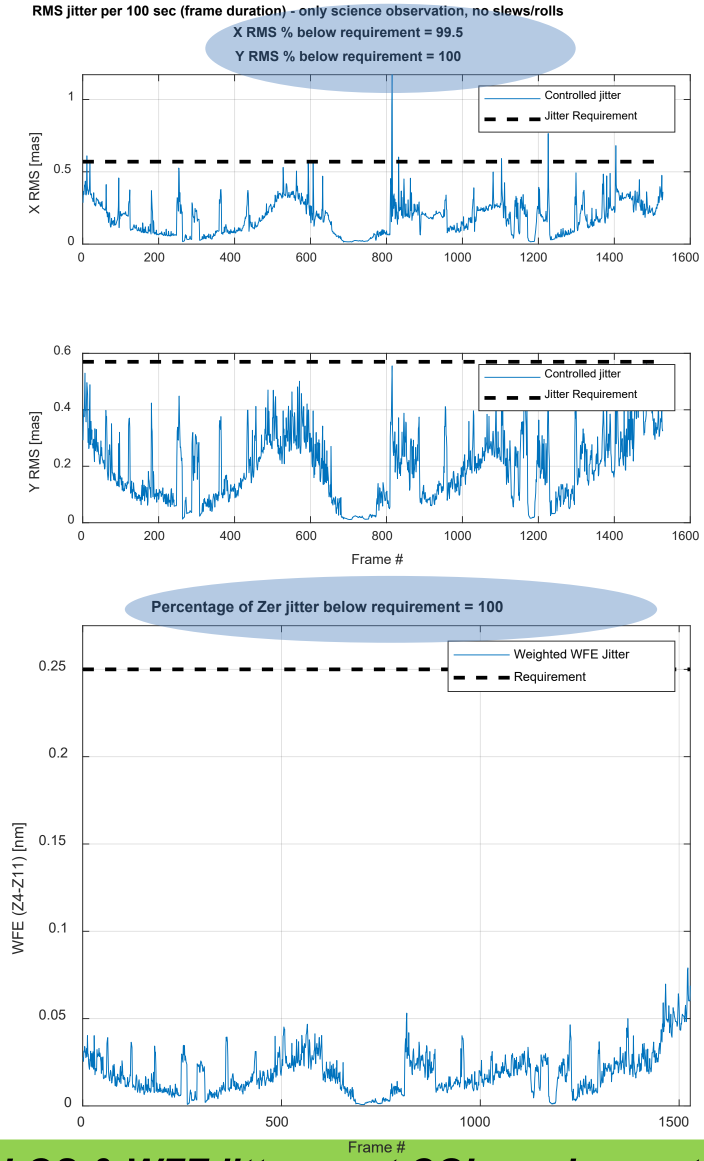
CGI Jitter vs Wheel Speed

To meet CGI jitter requirements, wheel speed range is constrained to within +/- 5 rev/sec.





CGI jitter for OS11



Transient analysis using JPL tool w/ OS11 wheel speed profiles applied to individual wheels

OS11 LOS & WFE jitter meet CGI requirement > 70% of the time

Model Validation Highlights

Thermal Model

Thermal Model Validation

Utilizes thermal vacuum (TVAC) balance and transition tests data to correlate steady-state and transient behavior

Verify temperatures are within required range for optical and signal-to-noise performance

Demonstrate heater tuning process and performance

Structural Model

Material Characterization

Leveraged extensive JWST material characterization

Provided additional testing as appropriate for key Roman materials

Dynamics Model Validation

1. Induced Vibration Measurements
2. Modal Survey for Stowed Dynamics
3. Isolation and Damper Performance Verification
4. Frequency Response Functions (FRFs) and Deployed Frequency

Distortion Model Validation

Leverage optical verification and alignment/distortion measurements to validate structural models

Dedicated sinusoidal thermoelastic model validation on OTA components (PMA, SMST, SMA, and FMS)

Optical Model

Optical Verification

Provide roadmap to generating "as-built" optical models

Provide warm and cold measurements in 1G to support cooldown distortion model validation

Summary and Future Work

- **Roman IM and optical Monte Carlo simulation results continue to show design meets key mission performance requirements, including stringent CGI stability requirements**
  - Combination of hardware, software, and operations achieves the CGI stability performance

- **Roman IM has a few key tests that will validate models for nanometer-level stability predictions**
  - Sinusoidal thermal distortion model validation of telescope components
  - Payload heater tuning and temperature stability during Spacecraft + Payload TVAC test

- **Future Work**
  - Additional analyses are planned to further understand system sensitivity, reduce conservatism, and address any stability concerns
  - Support and crosscheck model validation test analysis
  - Prepare for commissioning analysis