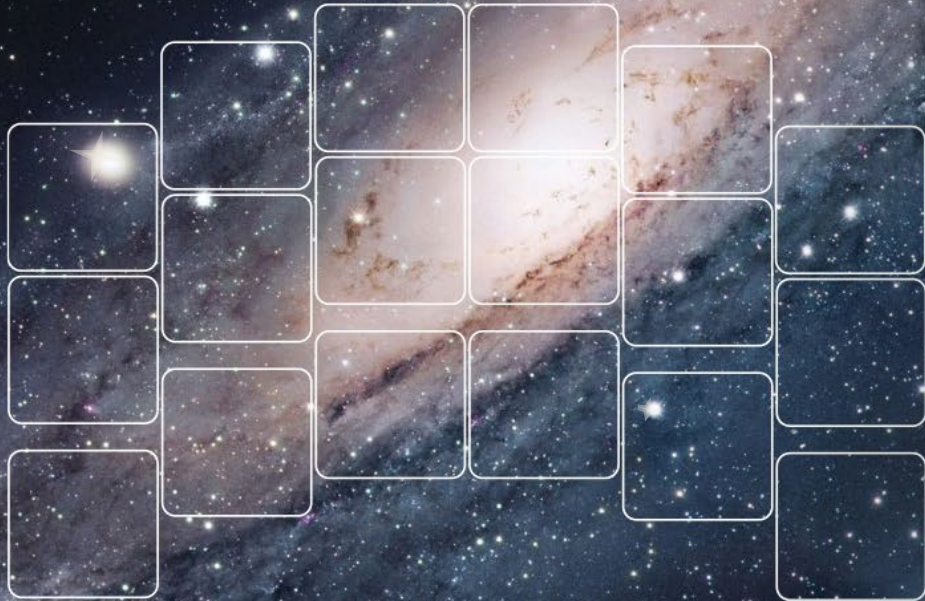


NANCY GRACE ROMAN



SPACE TELESCOPE

IEEE Aerospace Conference 2025

Achieving Stability – Systems Design and Analysis of the Roman Space Telescope

March 3, 2025

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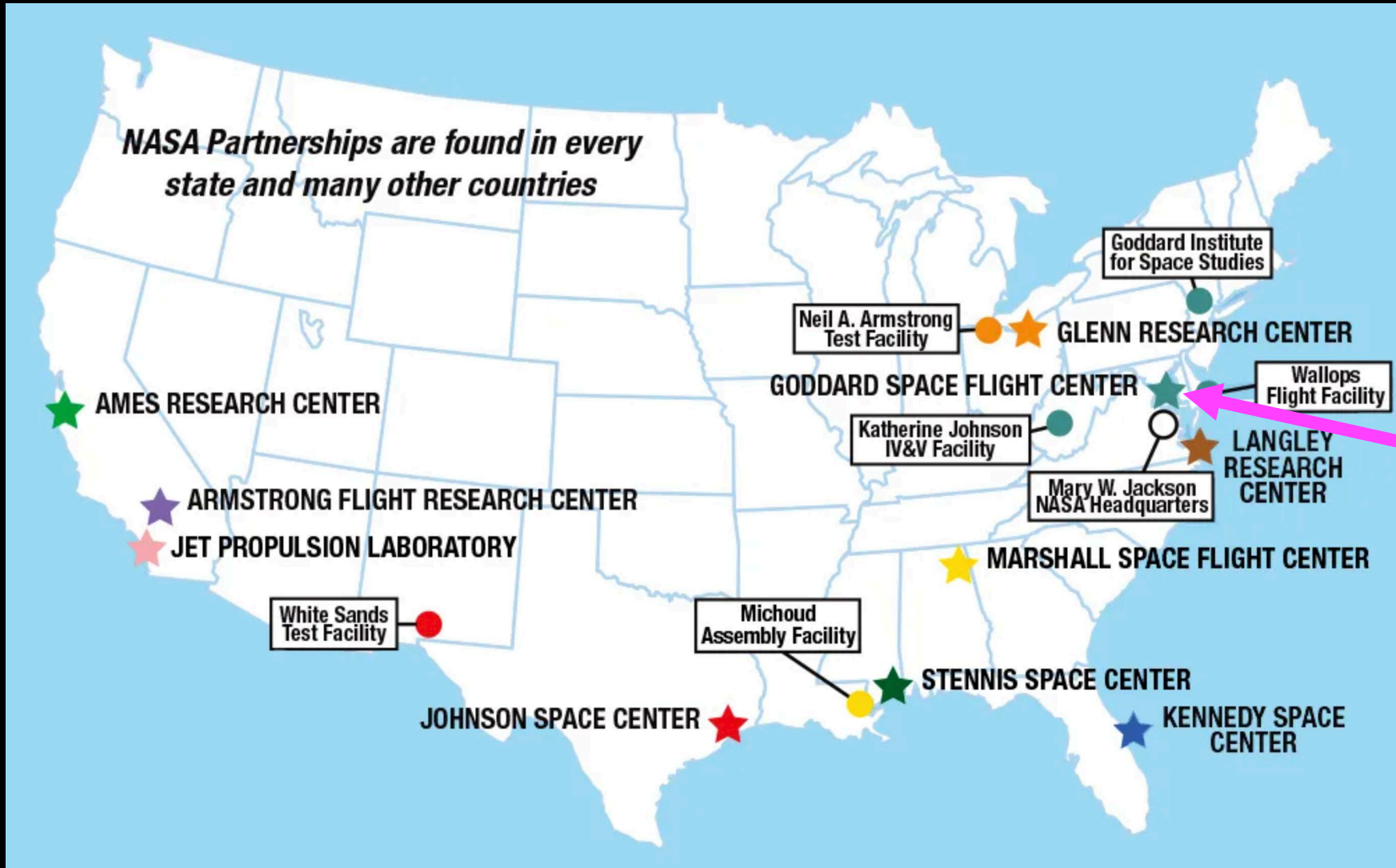
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Agenda

1. Overview of the Roman Space Telescope
2. Image Quality Requirements and Error Sources
3. Integrated Modeling

NASA has many locations in the USA...




We work at
Goddard, near
Washington DC

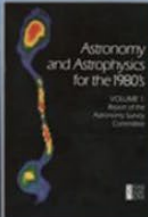


Astrophysics

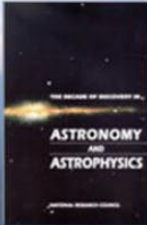
Decadal Survey Missions




1972
Decadal Survey
Hubble



1982
Decadal Survey
Chandra



1991
Decadal Survey
Spitzer



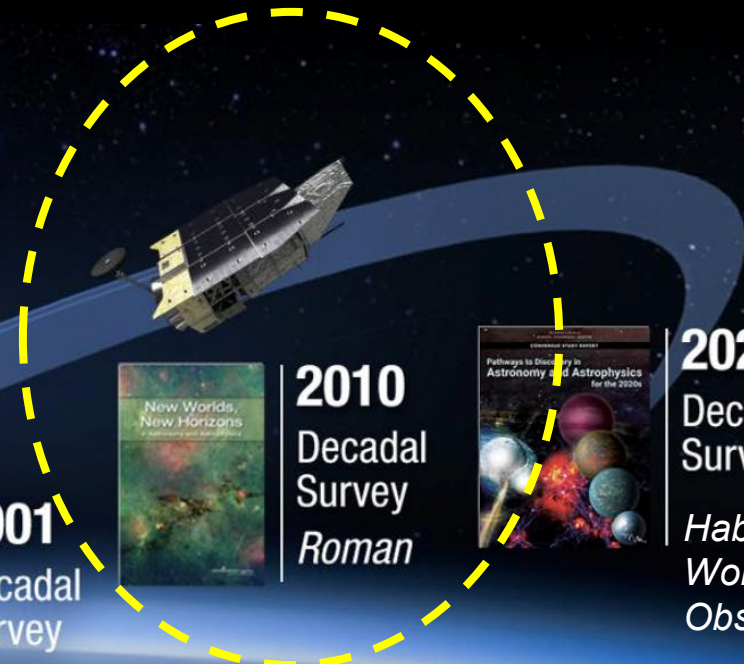
2001
Decadal Survey
Webb



2010
Decadal Survey
Roman



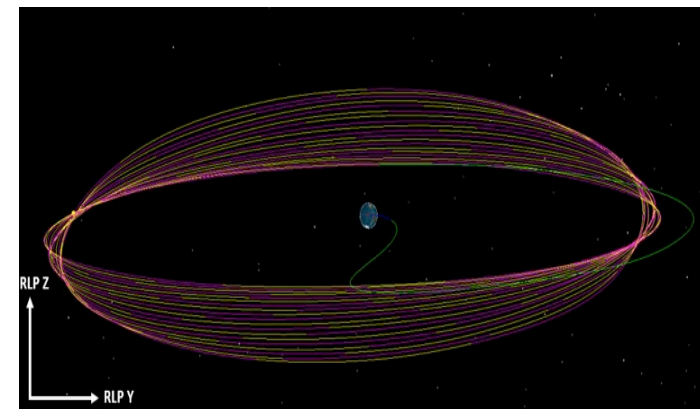
2021
Decadal Survey
Habitable Worlds Observatory



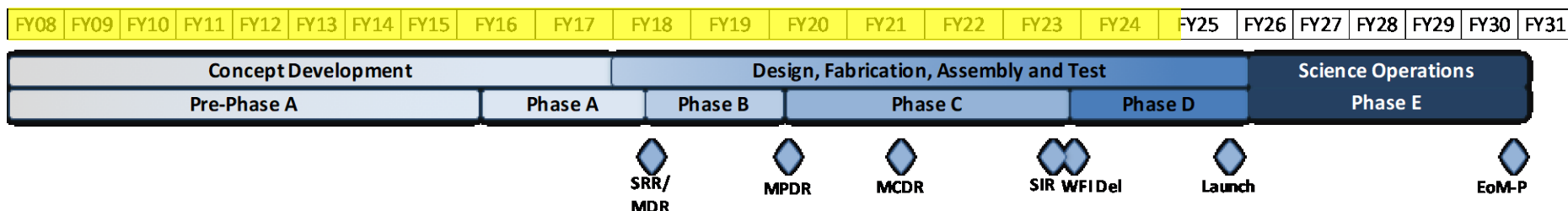
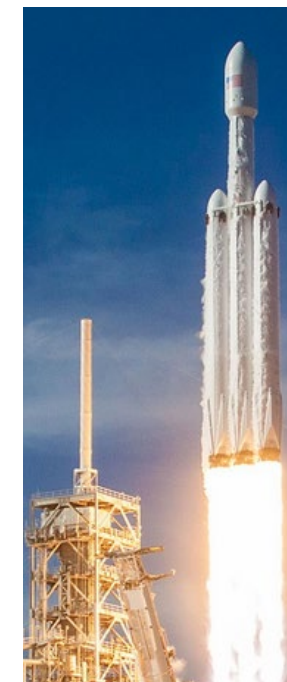
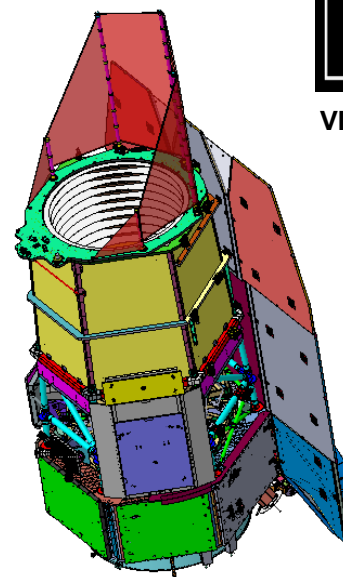
Roman Mission Overview



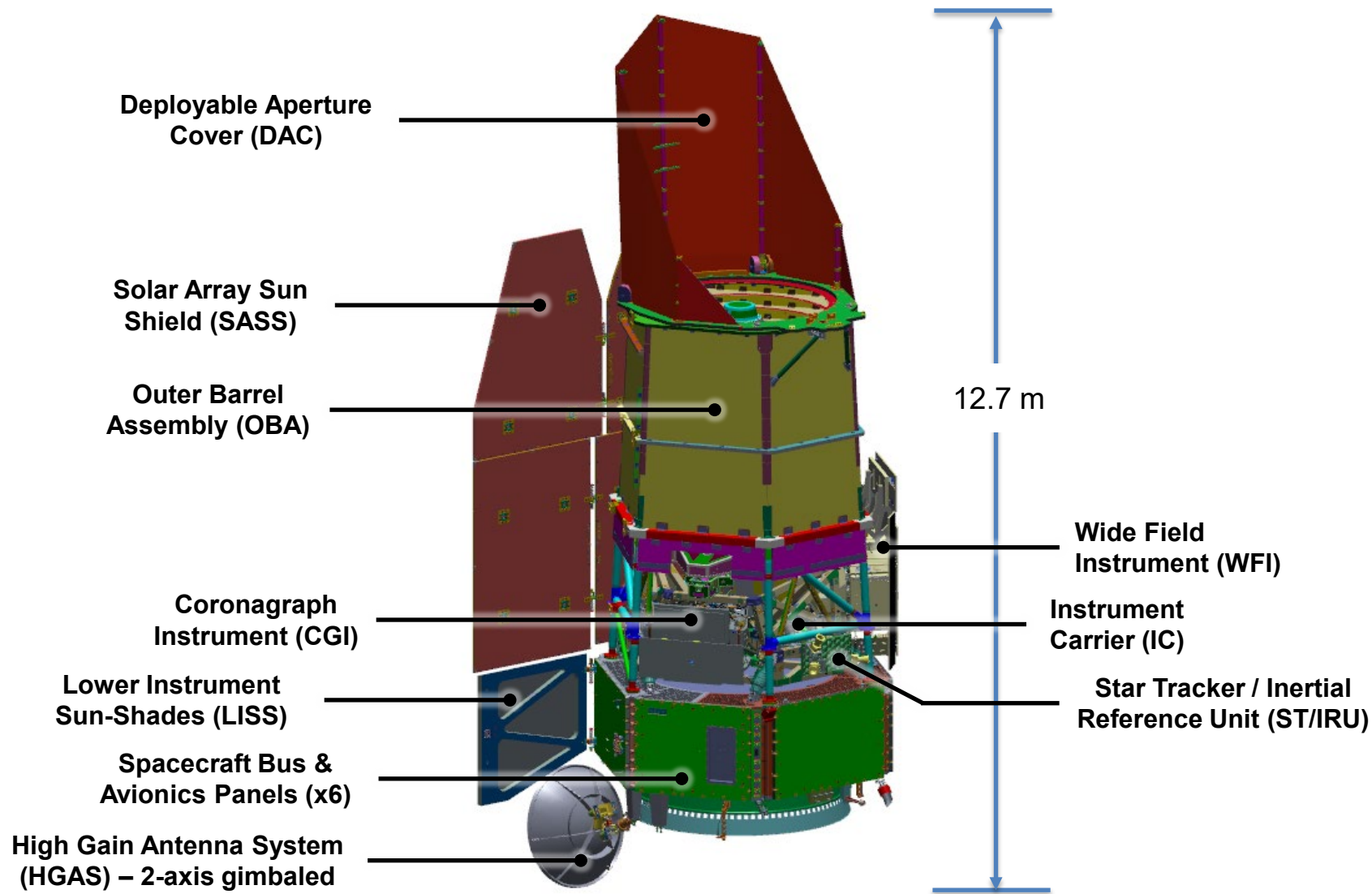
- **RST:** Nancy Grace Roman Space Telescope (Class A)
- **Mission:** Wide-Field Infrared Survey
- **Objectives:**
 - Determine nature of the dark energy driving the current accelerating universe expansion
 - Perform statistical census of planetary systems through microlensing survey
 - Survey the NIR 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

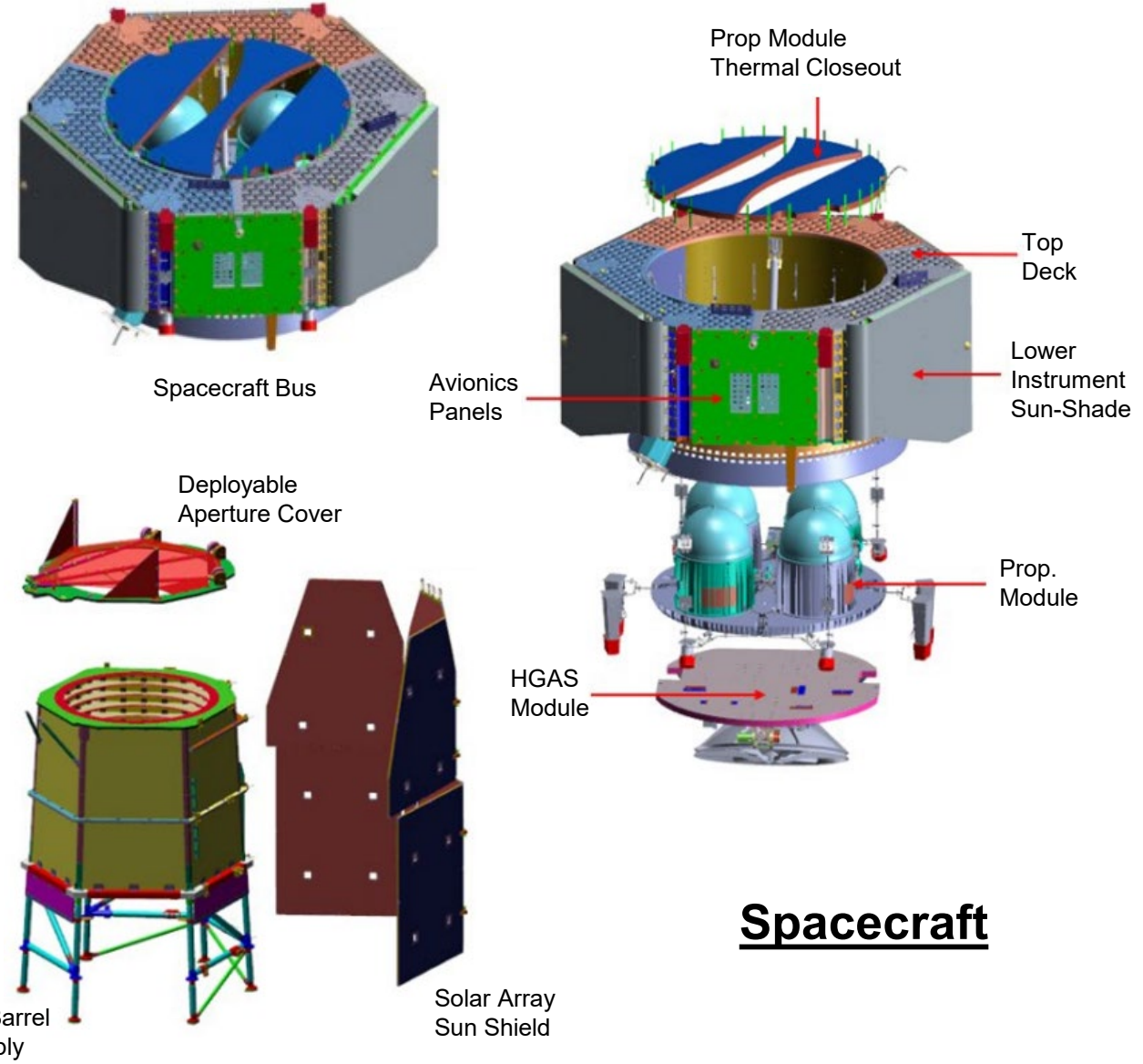
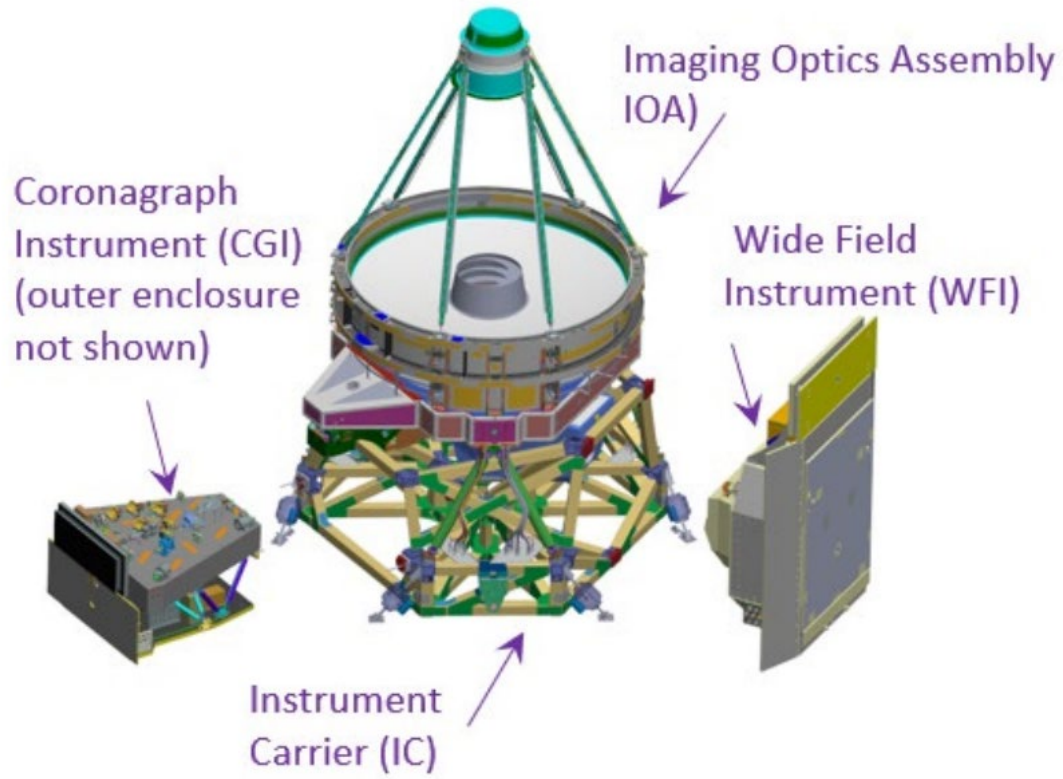


Observatory Overview



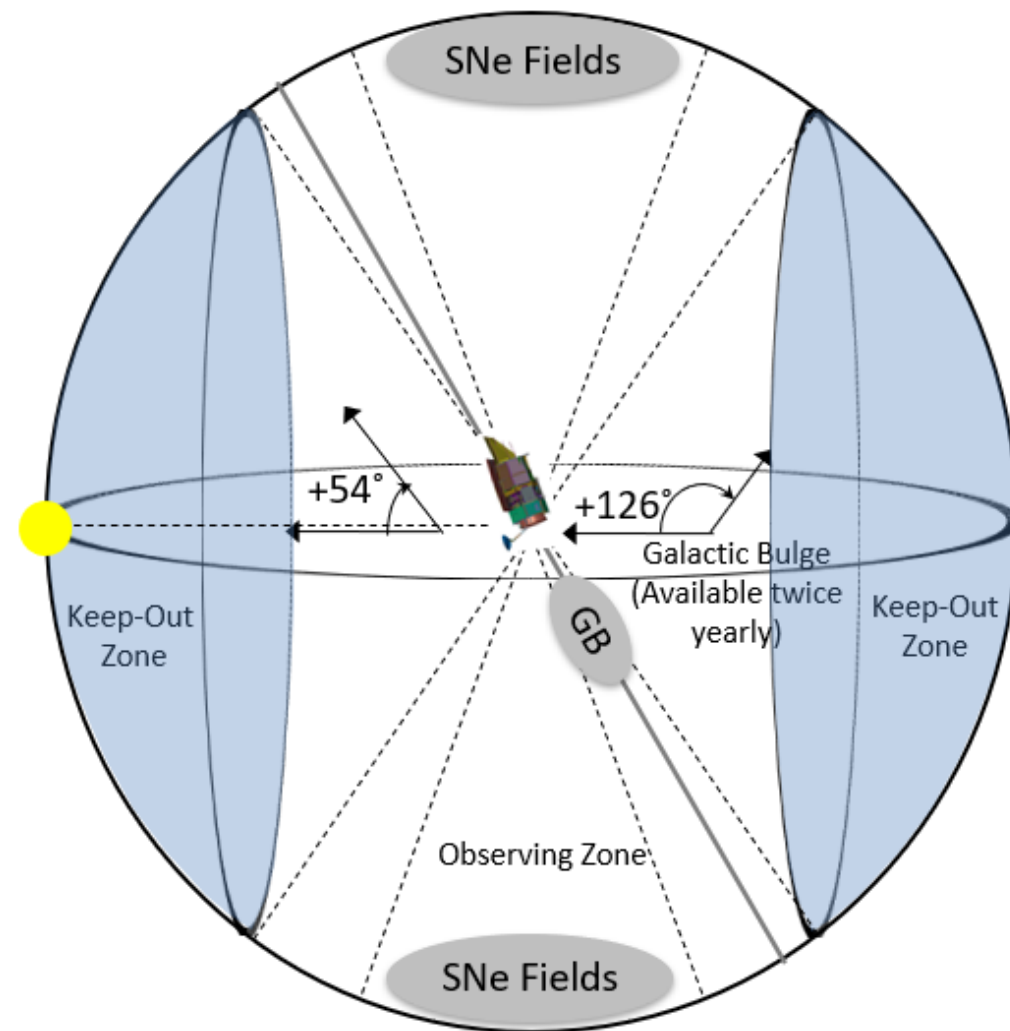
Observatory Overview

Payload



Spacecraft

- The Roman Mission consists of a five-part observing program:
 - **High Latitude Wide Area Survey:** Spectroscopic & Imaging sky survey for Baryon Acoustic Oscillation (BAO) / Redshift space distortion (RSD) & Weak Lensing/Galaxy Clustering
 - Mapping $>1,700 \text{ deg}^2$, observations of $\sim 140 \text{ sec}$ (imaging) or $\sim 300 \text{ sec}$ (spectroscopy)
 - **High Latitude Time Domain Survey:** Multiple visits to fields at high ecliptic latitudes to discover and track Supernova
 - 30 hours of imaging and spectroscopic observations every 5 days
 - **Galactic Bulge Time Domain Survey:** Repeated visits to fields near the Galactic bulge to monitor planetary microlensing events
 - Repeated viewing of 7 fields every 15 minutes for 60 days
 - **Exoplanet Coronagraphy:** Targeted observations of nearby stars for technology demonstration of high-contrast imaging and spectroscopy
 - **General Observer:** Allocated time for proposers to observe targets anywhere within the field of regard
 - All portions of the sky in the FOR are visible during otherwise-unallocated time



Roman Field of Regard (FOR)

- For space telescopes like Roman, two critical metrics determine optical system image quality
 - Wavefront Error (WFE), represents the deviation of the actual optical wavefront from its ideal shape
 - Line-of-Sight (LOS) error, results in image motion or “blur”

Wide Field Instrument Stability Requirements

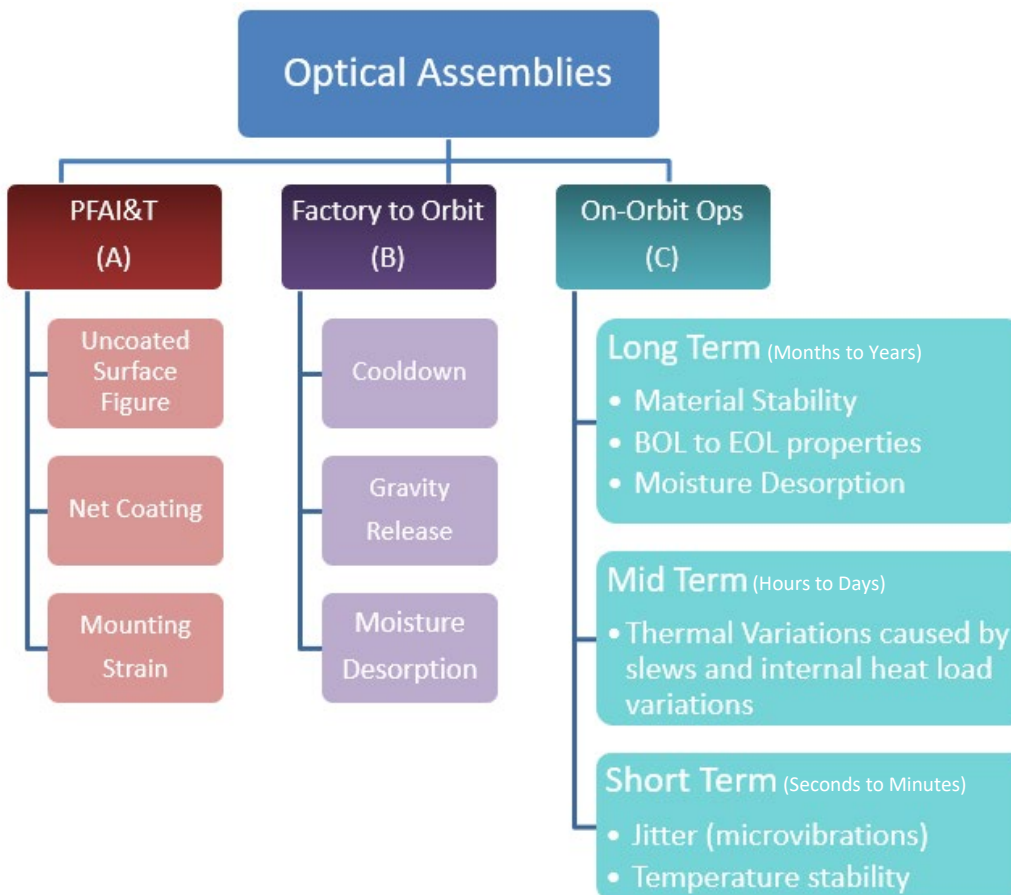
Wide Field Stability Descriptions	Allocation	Duration
WFE: Ground-to-Orbit Change	28.0 nm	One time change
WFE: On-Orbit Variation	33.1 nm	Hours-to-months
WFE Short-Term Stability ¹	1.0 nm ★	180 sec
LOS Jitter	12.0 mas	180 sec

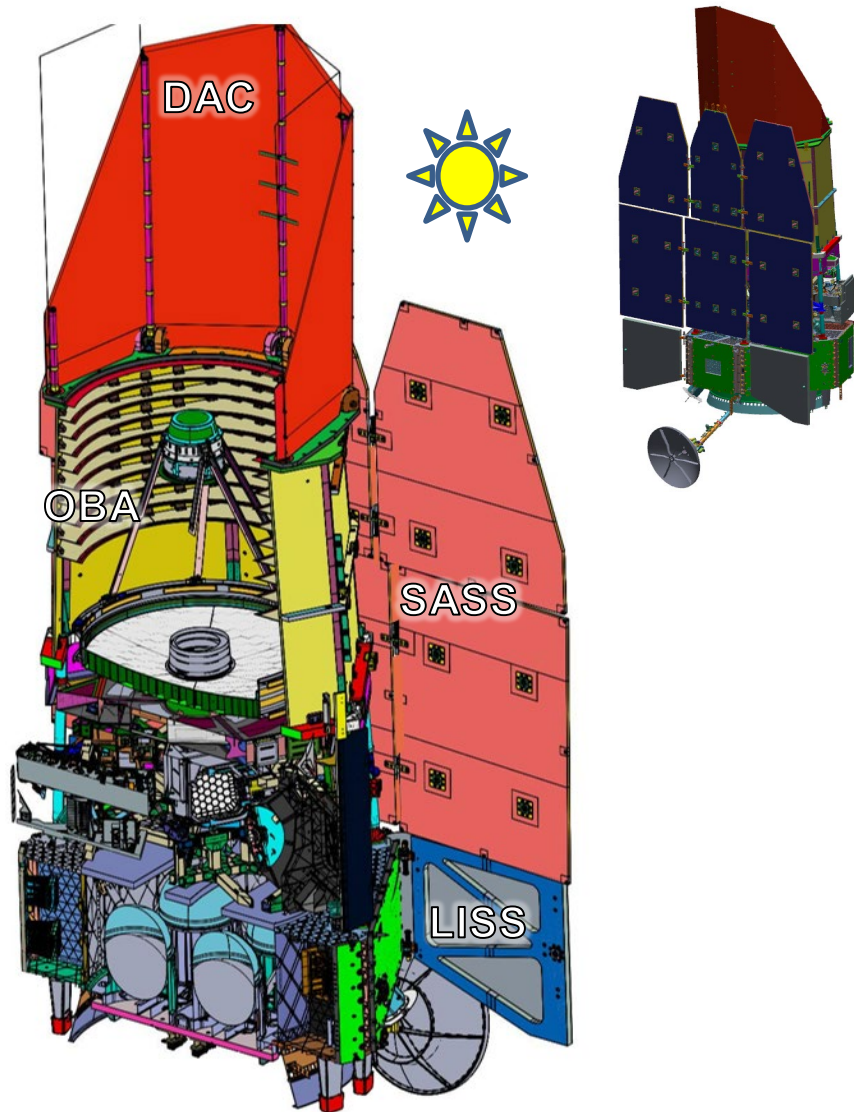
1. Main driving stability requirement, derived from the HLWAS Imaging Mode ellipticity knowledge requirement.

Coronagraph Instrument Stability Requirements

Coronagraph Stability Descriptions	Allocation RMS	Duration
Focus Drift	10.0 nm 4.0 nm	100 hours 10 hours
WFE Drift, Z5-Z11	0.25 nm	10 hours
WFE Drift, filtered Z4-Z11	0.15 nm	10 hours
WFE Jitter	0.25 nm	100 sec
LOS Jitter	0.57 mas	100 sec

- WFE and Alignment budget organizes errors into 3 categories
 - Production, Fabrication, Assembly, Integration, and Testing (PFAI&T)
 - Ground-to-orbit (launch + commissioning): **Cooldown**, **Gravity Release**, **Moisture Desorption**
 - On-orbit Variations (post commissioning):
 - Distortion Effects (**thermal stability**, **material stability**, **moisture desorption**)
 - Jitter (microvibrations)



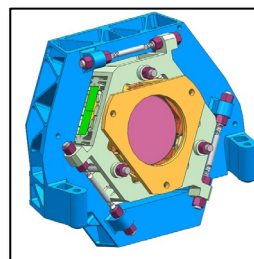


- **Ground-to-orbit**
 - Place optics at predicted 1g and warm positions to offset gravity and cold-shift effects
 - Cold figure primary mirror
 - Thermal control system
 - Kinematic interfaces (FOA struts and WFI outer enclosure)
 - Flight Alignment compensators

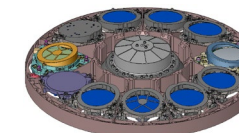
- **Thermal/Thermoelastic Stability**
 - Mechanical sun shields
 - Solar Array and Sun Shield (SASS)
 - Deployable Aperture Cover (DAC)
 - Low emissivity on primary mirror facing side
 - Outer Barrel Assembly (OBA)
 - Lower Instrument Sun-Shade (LISS)
 - Thermal control systems
 - OBA, IOA, IC, WFI, CGI, and SC Bay 4 (reaction wheels)
 - Active optics control
 - CGI adaptive optics: fast steering mirror, focus control mechanism, and deformable mirrors
 - ConOp constraints
 - Reduce slew size and observing plans

- **Long-term material and/or dimensional stability**
 - Flight alignment compensators

- **Reaction Wheel Assemblies**
 - Six Honeywell HR18-250 RWAs
 - *Continuous operation*
- **High Gain Antenna System (HGAS)**
 - Two axis gimbal using low-detent stepper motors to provide gimbaling pointing
 - *Rarely would need to be actuated 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
 - *Parallel WFI imaging planned does not have to meet optical stability requirements*



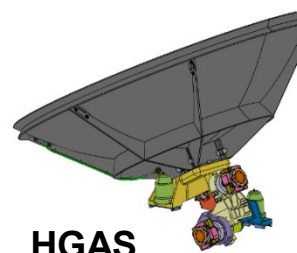
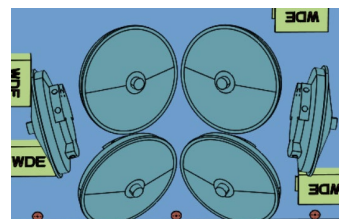
CGI Fast Steering Mirror



WFI Element Wheel

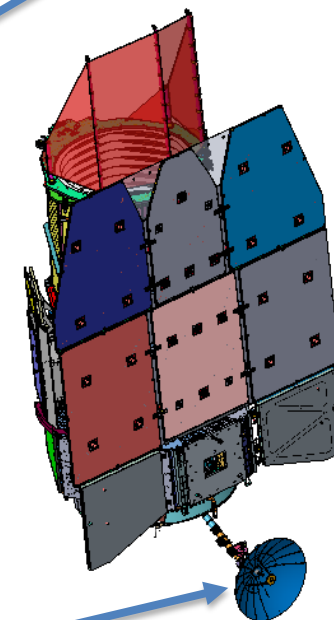
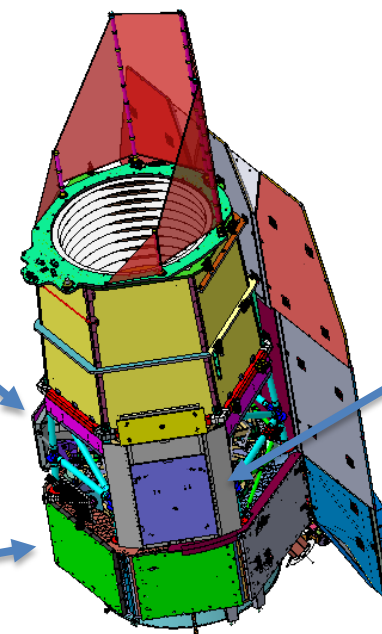


RWAs



HGAS

(two gimbal actuators control elevation and azimuth position of dish)



Mechanical

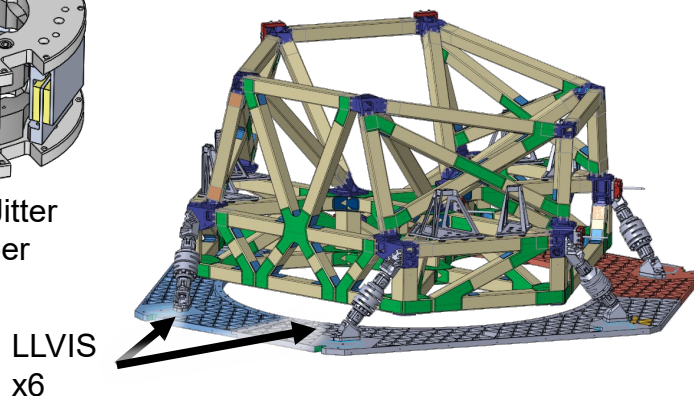
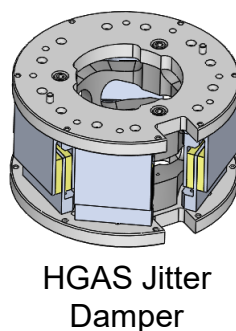
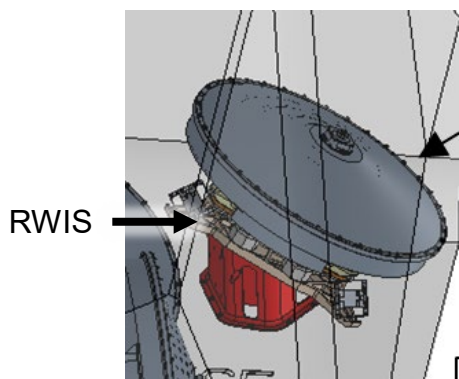
- Launch Loads and Vibration Isolation System (LLVIS)
 - Between the Spacecraft and Instrument Carrier
 - ~20 Hz first mode, effectively isolates HGAS/RWIS
- RWA fine balance option for reduced static/dynamic disturbance
- Reaction Wheel Isolation System
 - Each RWA is individually isolated at approximately 2 Hz
- HGAS Jitter Damper
 - Damps out lowest frequency HGAS boom modes
- Solar Array Sun Shield Tuned Mass Dampers
 - Damp out SASS modes excited during HGAS operation
 - Total of 4 array on the SASS panels
- Requirements to bound deployed mode frequencies

Electrical

- HGAS actuator microstepping
 - 16 microsteps/step by varying 3 winding voltages
- HGAS low detent stepper
 - Winding re-designed to improve powered torque to detent ratio

Software

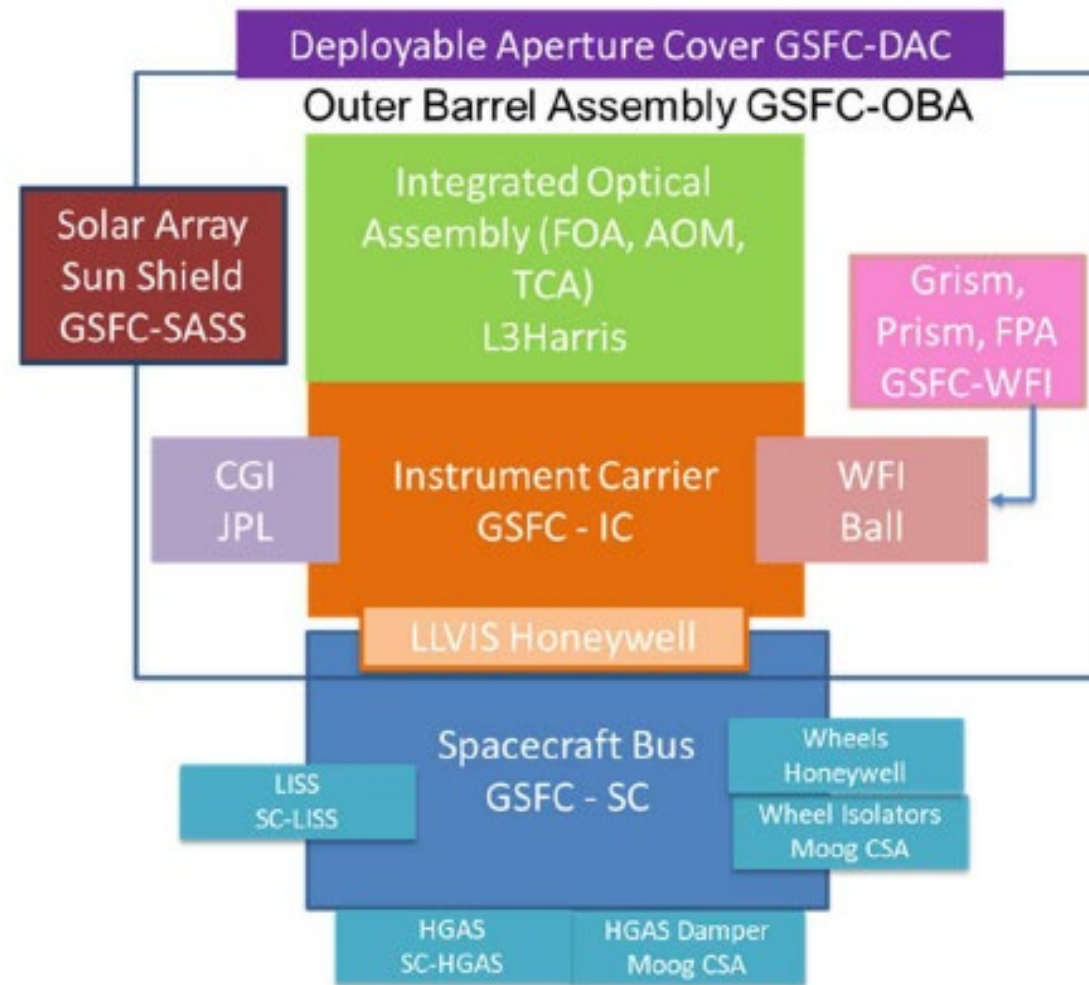
- RWA speed limit during science
 - Limited to 36 rev/sec to avoid exciting resonant modes above this frequency
- RWA separation algorithm
 - ACS is using an L-infinity wheel distribution algorithm that drives four wheels to same speed
 - ACS is enforcing 1 Hz (60 RPM) separation between the four wheels
- HGAS step avoidance during inertial hold
 - ACS is designing the HGAS pointing algorithm and slew profile to minimize the need to step during imaging
- HGAS step rate keep out zone
 - Accelerate through mode frequencies to avoid ringing up the modes



Integrated Modeling Overview

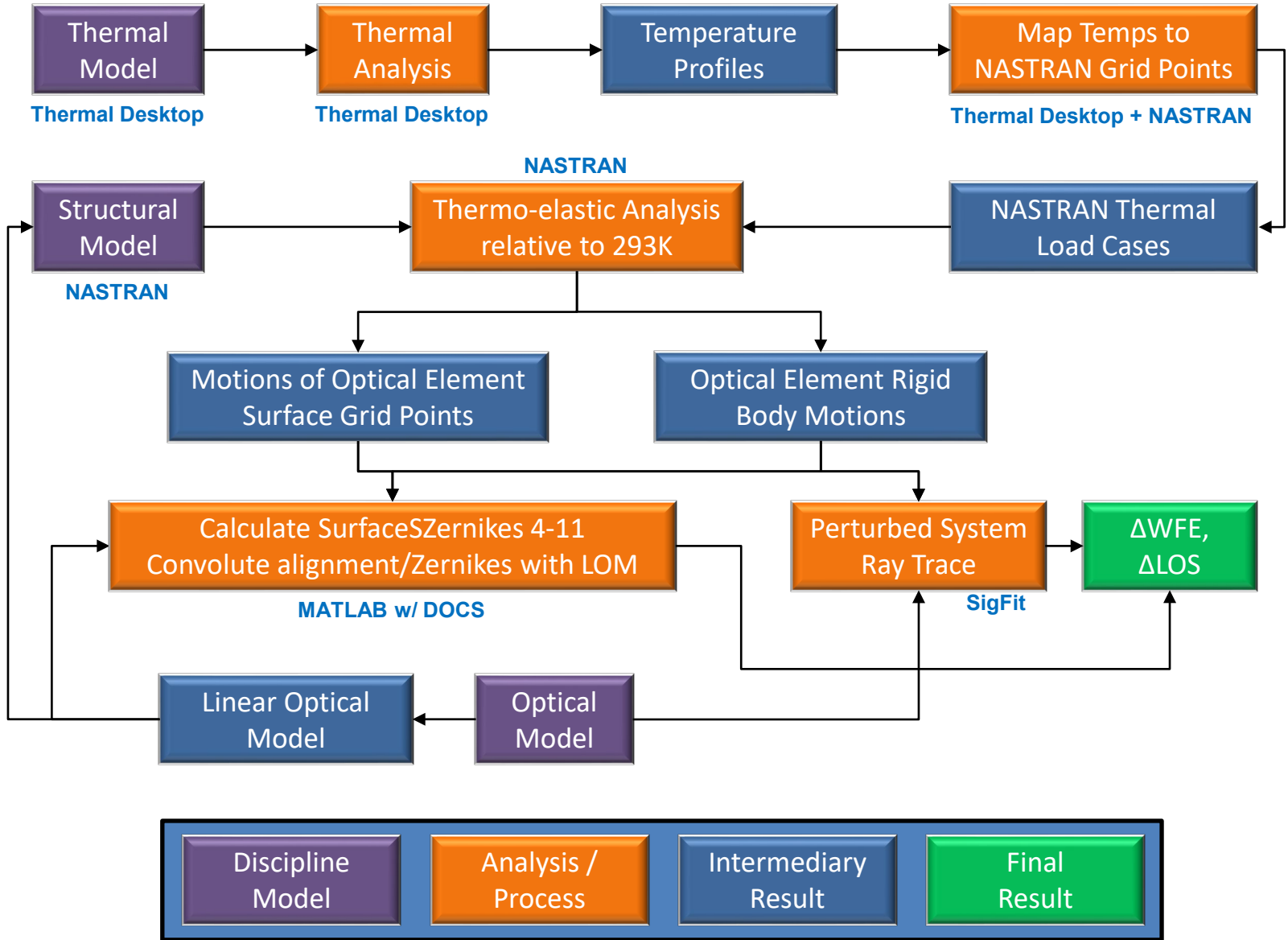


- **IM is a cross-disciplinary analysis that captures complex interaction among different disciplines, enables accurate system predictions, and supports complex design trades**
- **On Roman, IM is responsible for verifying by analysis performance requirements that cannot be practically verified by test or can only be partially verified by test**
 - On-orbit, end of life optical quasi-static wavefront error (WFE), alignment, and stability are key performance requirements verified by IM
- **Vertical model integration process generates thermal, structural distortion, and optical models for the Observatory**
 - Final integrated structural model goes through additional development to generate configurations that support variety of distortion effects
- **Horizontal model integration couples discipline models/analyses representing different physical processes to arrive at image quality metrics**
 - Structural-Thermal-Optical (STOP)
 - Moisture desorption (composite dryout)
 - Gravity sag
 - Jitter (microvibrations)



Roman Observatory Model Integration

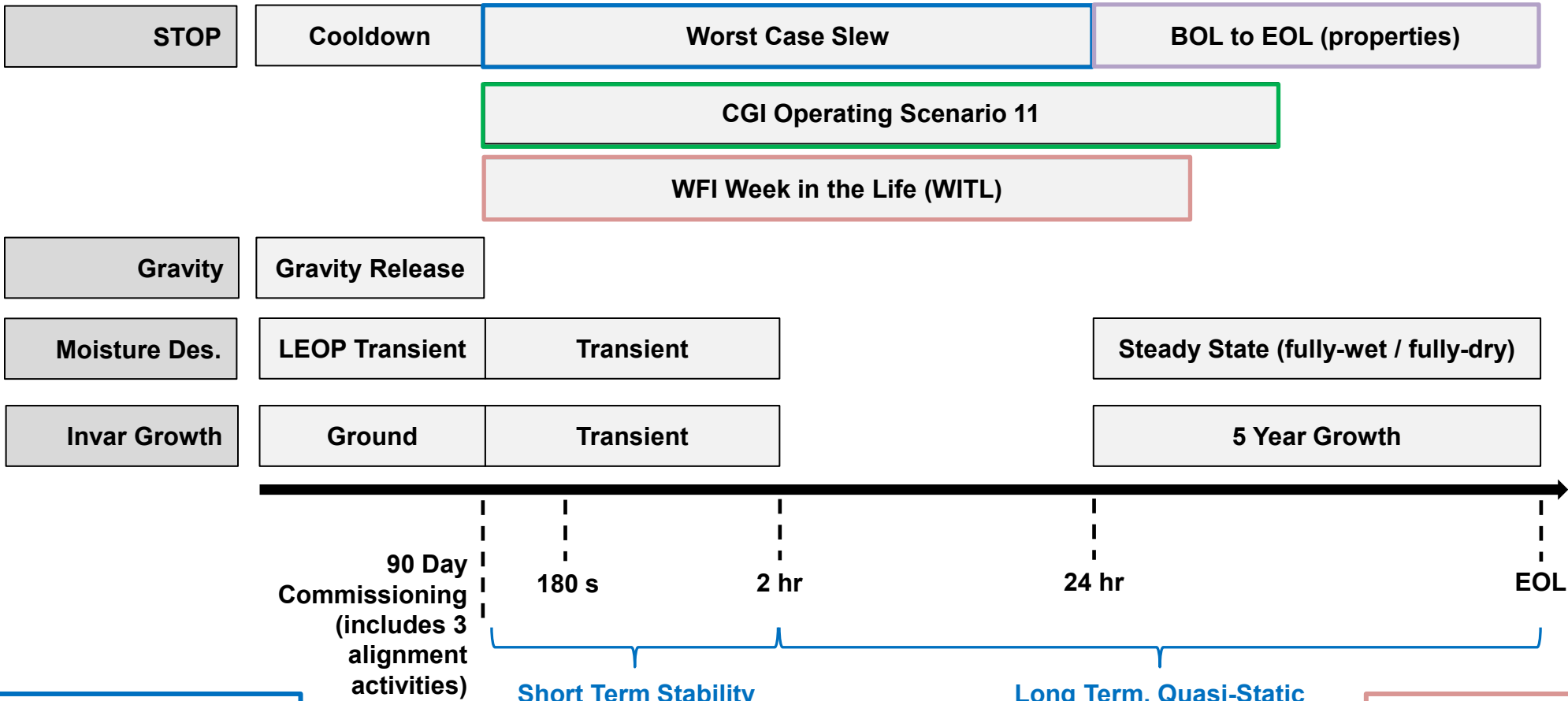
STOP/Distortion Analysis Process



Distortions can be fed along two parallel paths to compute optical response:

- First path uses a Code V optical model with SigFit software to compute ray traces
- Second path uses a Linear Optical Model (LOM) with sensitivities derived from the Code V optical model

STOP/Distortion Analysis Cases

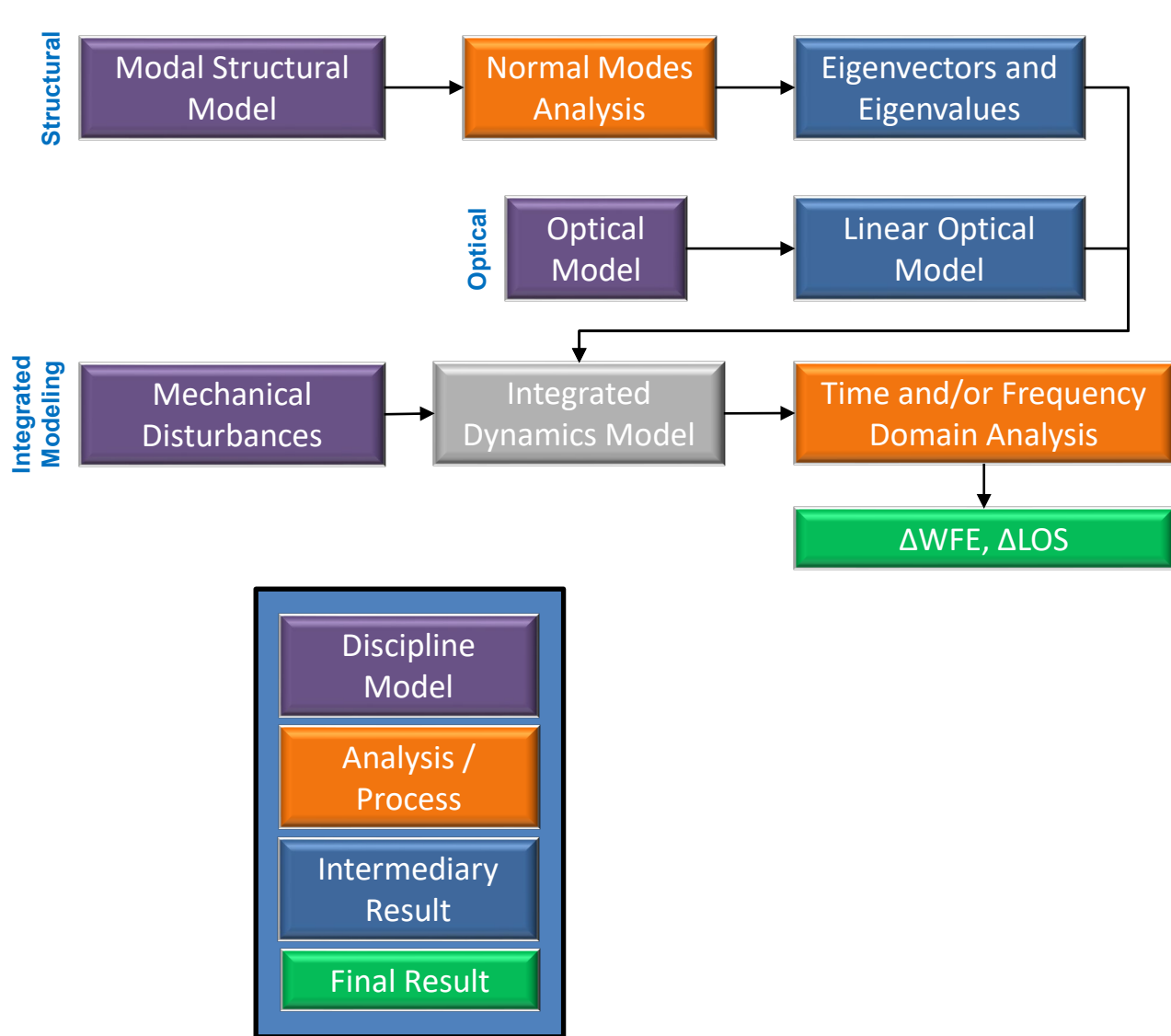


* Worst case slew: defined by 2 attitudes that generate the largest WFE difference
 * Use sliding windows to predict stability performance

BOL to EOL: capture effects due to thermal property changes from BOL to EOL

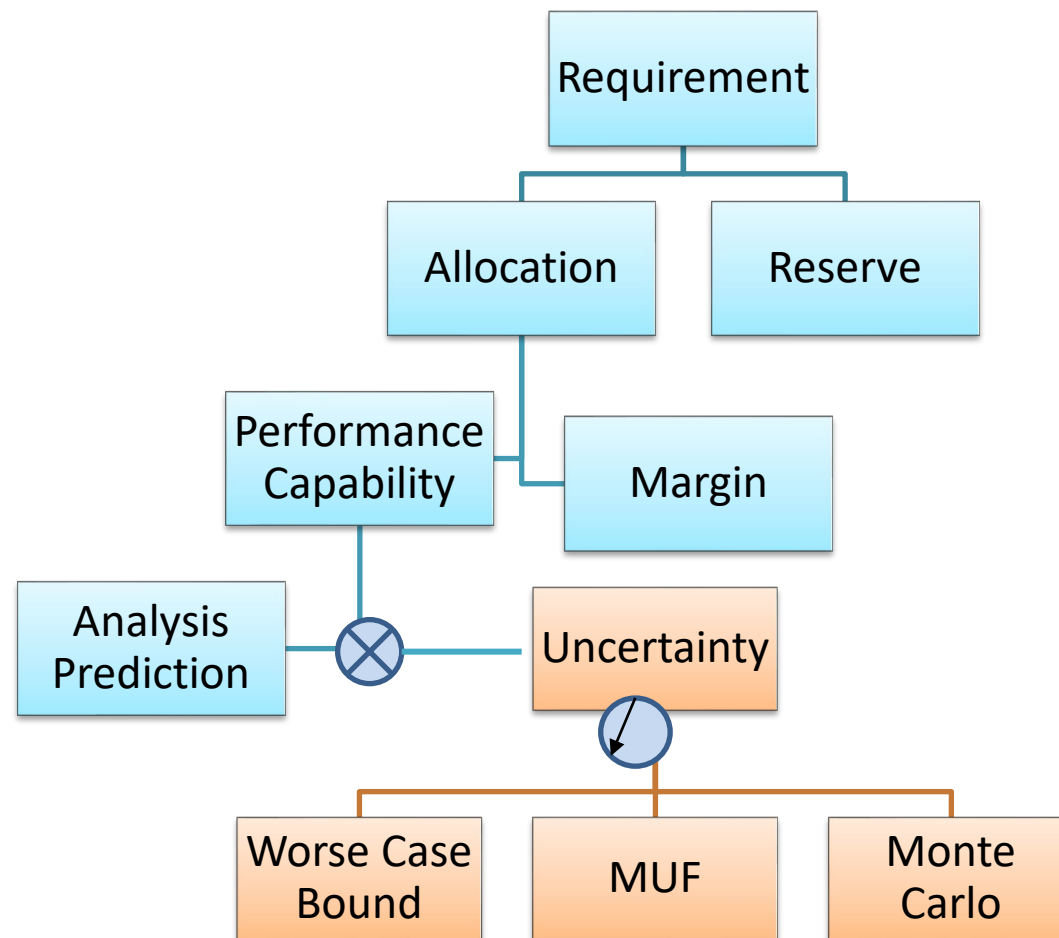
OS-11: scenario defined by CGI team for verifying CGI stability requirements

* WITL: provided by WFI science team to represent realistic survey scenario
 * Use this case to show margin against worst case slew



- **Reaction Wheel analysis**
 - Operates in frequency domain, provides ability to run large number of wheel speed samples efficiently
 - Analysis for CGI also includes a transient time domain analysis based on the operational scenario wheel speed profile applied to individual wheels
- **High Gain Antenna Gimbal Actuator analysis**
 - Operates in time domain given non-linear stepper motor behavior
 - High complexity as slew characteristics depend on point in orbit and location of astronomical target
 - Each slew is unique in terms of angle, speed, and phasing between elevation and azimuth
 - Case relies instead on a 24-hour sample of an observing scenario as baseline to evaluate jitter
- **IEEE Aeroconference 2025 papers/presentations:**
 - Parker Lin, “Measuring and Mitigating Roman Space Telescope Reaction Wheel Imbalance Forces and Torques”
 - David Schwartz, “Silent Steps: Mitigation and Analysis of Stepper Motor Induced Jitter on the RST”
 - Cory Smiley, “Managing TVAC Vibration for Optical Testing of the Roman Space Telescope”

- **For requirement verification by analysis, 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.)
- **Verification by analysis requires verified and validated models**
 - Math Model Guidelines
 - System Analysis and Model Validation Plan

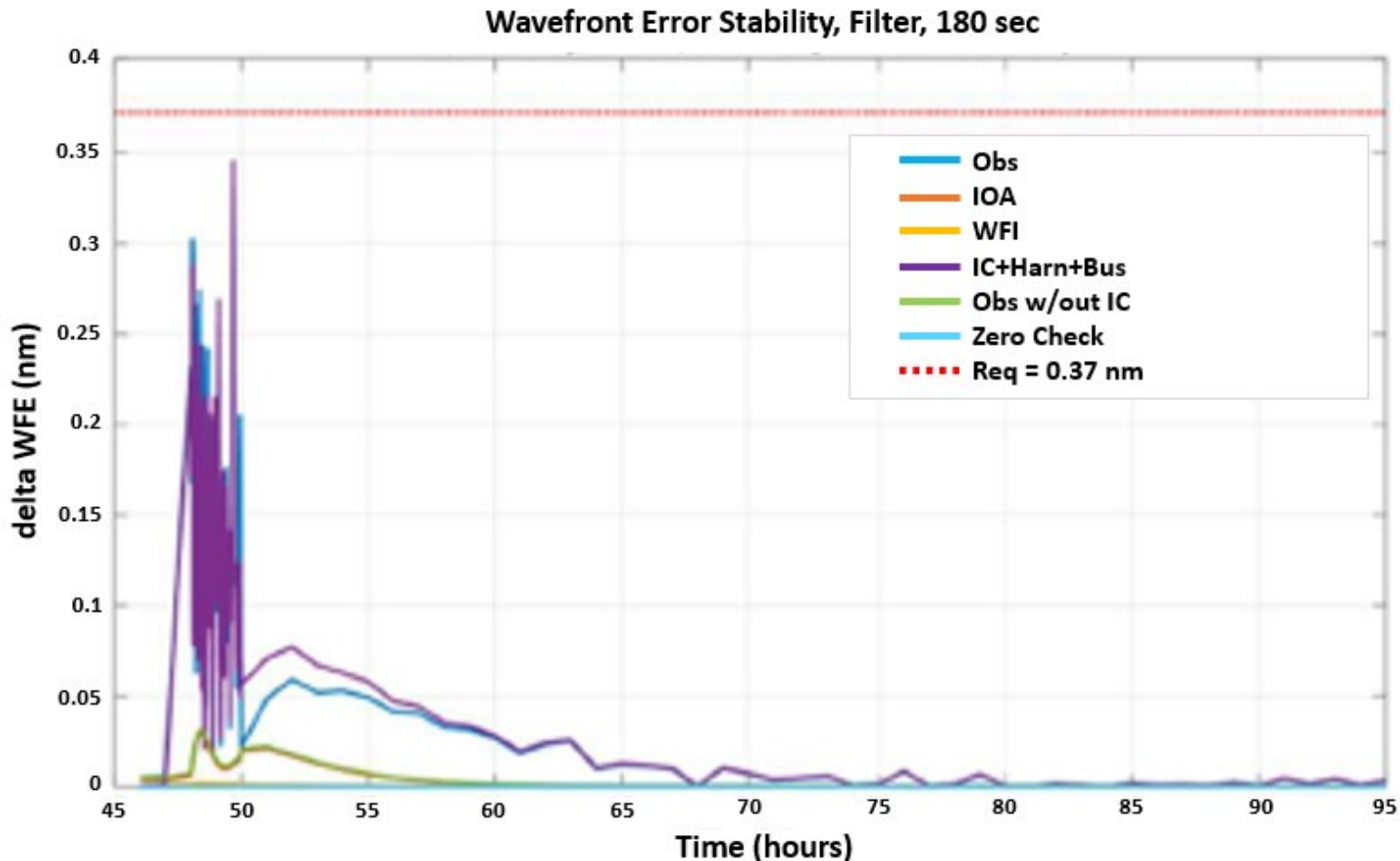


Wide Field Stability Predictions

Wide Field Stability Descriptions	Allocation	CBEs
WFE: Ground-to-Orbit Change	28.0 nm	17.1 nm
Cooldown	23.5	17.0
Gravity Release	15.2	1.7
WFE: On-Orbit Variation	33.1 nm	7.6 nm
Thermal Variation	24.3	7.2
Moisture Desorption	14.9	1.2
Invar Growth	16.8	2.2
WFE Short-Term Stability	1.0 nm	0.9 nm
Thermal Variation	0.6	0.4
Moisture Desorption		0.0
Invar Growth		0.0
RWA Jitter	0.8	0.8
HGAS Jitter	0.2	0.1
LOS Jitter	12.0 mas	10.6 mas
RWA Jitter	11.0	9.4
HGAS Jitter	4.0	5.0

Coronagraph Stability Predictions

Coronagraph Stability Descriptions	Allocation	CBEs
Focus Drift		
100 hours	10.0 nm	9.4 nm
10 hours	4.0 nm	1.1 nm
Z5-Z11 WFE Drift	0.25 nm	0.06 nm
Filtered WFE Drift (Z4-Z11)	0.15 nm	0.03 nm
WFE Jitter	0.25 nm	0.1 nm
LOS Jitter	0.57 mas	0.57 mas
	>70% of time	>99.5% of time



Sample Results Plot, STOP Analysis
WFI Channel Short Term Stability over Worst Case Slew (180s)

- **Verification by analysis requires verified and validated models**
- **Definition from NASA Modeling and Simulation Standard (NASA-STD-7009A w/Change 1)**
 - Model Verification: The process of determining the extent to which an M&S is compliant with its requirements and specifications as detailed in its conceptual models, mathematical models, or other constructs.
 - Roman Math Models Guideline
 - Crosscheck and independent analysis
 - Model Audit Team
 - Model Validation: The process of determining the degree to which a model or a simulation is an accurate representation of the real world from the perspective of the intended uses of the Modeling & Simulation (NASA-STD-7009A w/Change 1)
 - Roman System Analysis and Model Validation Plan
- **General approach is to correlate models at lower levels and use higher-level tests for model validation and interface model correlation**
 - Validation roadmaps show this flow for:
 - Thermal (steady state and transient)
 - Thermal distortion (cooldown and long-term)
 - Thermal distortion (short-term stability)
 - Gravity Sag/Release
 - Dynamics
 - Optical

Summary



- **All Roman flight hardware is now physically at Goddard Space Flight Center**
 - All payload flight elements delivered to system I&T in 2024 with Spacecraft Bus + Payload (SCIPA) integration completed late 2024
 - SCIPA TVAC test planned for summer 2025
- **Post-CDR IM results show quasi-static wavefront error (WFE), optical alignment, and stability requirements are met with MUFs and reasonable margin**
 - IM is currently working through flight analysis Cycle 4.1, inclusive of many subsystem level validated models
 - Cycle 4.1 results posted to-date continue to show allocations are met with healthy margin
- **Analysis and correlation efforts will continue through 2025, with final “run for the record” analysis work to support Roman Pre-Ship Review in early 2026**



SCIPA (foreground, R) and OBA (background, L), in the SSDIF, Jan 2025